Chair of Energy Network Technology

Doctoral Thesis

Decarbonisation of Austria: Exergy Effiency and Sector Coupling

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AFFIDAVIT

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KURZFASSUNG

Die Klimakrise ist eine der größten Herausforderungen unserer Zeit. Um die globale Erwärmung unter 2°C zu halten, müssen die weltweiten Treibhausgasemissionen (THG-Emissionen) in den nächsten zwei bis drei Jahrzehnten sehr stark reduziert werden. In der EU sind etwa 77% der gesamten THG-Emissionen auf die Nutzung fossiler Brennstoffe zurückzuführen. Grundsätzlich kann eine Reduzierung der THG-Emissionen durch Verhaltensänderungen, Energieeffizienzmaßnahmen oder den Wechsel von fossilen auf erneuerbare Energiequellen erreicht werden.

Das derzeitige Regierungsprogramm von Österreich strebt eine vollständige Dekarbonisierung bis 2040 an. Allerdings gibt es bisher keine umfassende Strategie zur Erreichung dieses Ziels. Die vorliegende Dissertation adressiert wie viele andere Publikationen eine nationale Dekarbonisierung, fokussiert sich jedoch auf zwei Aspekte, welche bisher weder national noch international untersucht worden sind. So wird einerseits jener Technologiemix des gesamten österr. Energiesystems ermittelt, welcher die Gesamtexergieeffizienz maximiert. Andererseits wird der nationale Importbedarf erneuerbarer Gase bestimmt.

Für die Untersuchung dieser beiden Aspekte wurde das gesamte österr. Energiesystem berücksichtigt, inklusive aller Wirtschaftssektoren, Nutzenergiekategorien sowie der gesamten Energiewandlungskette von Ressourcen bis hin zu Energiedienstleistungen. Zunächst wurde der Status quo des österr. Energiesystems, samt dem derzeitigen Bedarf an Energiedienstleistungen, erhoben. Anschließend wurde ein Optimierungsmodell entwickelt, um den optimalen Technologiemix zur Deckung des gesamten derzeitigen Bedarfs an Energiedienstleistungen zu ermitteln. Im letzten Schritt wurden zwei Szenarios für die Jahre 2030, 2040 und 2050 untersucht, um den Gesamtbedarf an erneuerbaren Gasen sowie das nationale Potential an grünem Wasserstoff inkl. Kostenanalyse zu bestimmen.

Die Ergebnisse zeigen, dass in Österreich derzeit etwa 370 TWh/a an Exergie zur Deckung des gesamten Nutzexergiebedarfs (ca. 133 TWh/a) benötigt werden. Der Einsatz des optimalen Technologiemixes für das gesamte Energiesystem könnte die Gesamtexergieeffizienz von derzeit 36% auf 58% erhöhen. Für das zukünftige, vollständig dekarbonisierte Energiesystem werden primär Elektrizität und erneuerbare Gase benötigt werden. Während nahezu der Gesamtbedarf an Elektrizität national gedeckt werden kann, sind zumindest 41% (40 TWh/a) des gesamten erneuerbaren Gasbedarfs im Jahr 2050 zu importieren. Im gleichen Bezugsjahr in einem Business-As-Usual-Szenario wäre der Importanteil beinahe 100% (zwischen 210 und 250 TWh/a). Energieeffizienzmaßnahmen sowie Verhaltensänderungen können den zukünftigen Importbedarf reduzieren. Die Kosten von national produziertem grünem Wasserstoff werden mit jenen von importiertem grünem Wasserstoff vergleichbar sein.

ABSTRACT

The climate crisis is one of the greatest challenges of our time. To keep global warming below 2°C, worldwide greenhouse gas (GHG) emissions must be almost completely eliminated in the next two to three decades. In the EU, about 77% of total GHG emissions are caused by the utilisation of fossil fuels. In principle, GHG reduction can be achieved through behavioural change, energy efficiency measures or the replacement of fossil energy sources with renewable energy sources.

Austria’s current government program aims to fully decarbonisation by 2040. However, there is no comprehensive strategy to achieve this goal. Nevertheless, there are various studies, initiatives and publications available that addresses different aspects of the decarbonisation of Austria. This thesis also deals with the decarbonisation of Austria but focuses on two aspects that have not been covered before, neither nationally nor internationally. The first aspect is about the determination of the optimal technology mix throughout the entire energy system to maximise exergy efficiency. The second aspect is the investigation of the national renewable gas import demand.

To address these two aspects, the entire Austrian energy system, including all economic sectors, useful energy categories and the entire conversion chain from resource to energy service is considered. First of all, the status quo of the Austrian energy system was determined. This also involved the current demand for energy services. Then, an optimisation model was developed to identify the optimal technology mix for covering the total demand for energy services. In the last step, two scenarios were analysed for 2030, 2040 and 2050 to determine the total demand for renewable gases and the national potential of green hydrogen. This also includes a cost analysis.

The results show that currently about 370 TWh/a of exergy are required to cover about 133 TWh/a of useful exergy to fulfil all energy services. This corresponds to an exergy efficiency of 36%. Optimal technology mix throughout the entire energy system would increase the efficiency to 58%. The future decarbonised energy systems will be mainly based on electricity and renewable gases. According to the scenarios, while almost the entire electricity demand can be covered nationally, at least 41% (40 TWh/a) of the renewable gas demand has to be imported in 2050. In the same year, in the business-as-usual scenario, the import share would be close to 100% (between 210 and 250 TWh/a). The implementation of efficiency and sufficiency measures reduces the import demand for renewable gases. Nationally produced green hydrogen has comparable costs to imported green hydrogen.

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Lukas, in the beginning, I met you as the supervisor of my master's thesis. We shared an office for the entire period between the end of my master's thesis and the time when you left the chair. In total, about three and a half years. In addition, we had two 45-minute train commutes almost every working day. We grew together and became friends. At the office, we had a wonderful time together with endless amounts of sweets. I was able to learn much from you about scientific work, scientific writing and the focus on the essentials. Extensive discussions have solved lots of scientific problems. Even after you finished your PhD, you continued supporting me with many discussions and valuable feedback. I am indescribably grateful for the wonderful time we spent together in the office and for your extensive support. Your input has been crucial for this thesis.

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CONTENTS

NOMENCLATURE

Abbreviation

CExC	Cumulative Exergy Consumption
CHP	Combined Heat and Power Generation
CO	Carbon Monoxid
CO_2	Carbon Dioxid
CUED	Current Useful Exergy Demand
DFT	Discrete Fourier Transformation
EAA	Environment Agency Austria
EU	European Union
FEA	Final Energy Application
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIC	Gross Inland Consumption
H_2	Hydrogen
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
IEA	International Energy Agency
MES	Multi Energy Systems
NEFI	New Energy for Industry
NGO	Non-Governmental Organisation
PEC	Primary Energy Consumption
RES	Renewable Energy Source
WAM	With Additional Measures
WEM	With Existing Measures

1 INTRODUCTION

The climate crisis is one of the greatest challenges of our time. From the second half of the 19th century to the period between 2010 and 2019, the global surface temperature increased by 1.07°C [1]. Humans influence is unequivocally the main cause of global warming, mainly through the emission of greenhouse gases (GHG) [1]. According to scenario SSP1-2.6 (low GHG emissions)[1] or scenario SSP2-4.5 (intermediated GHG emissions)[2], GHG emissions will increase the global surface temperature by 1.8 or 2.7 °C by 2081-2100 compared to 1850-1900, respectively [1]. Increasing global surface temperature leads to many problems such as the increase in frequency and intensity of weather extremes, changes in the global water cycle, reduction of permafrost and snow cover [1].

Due to these massive impacts, various agreements and decisions have been taken to address the climate crisis. One of the most important is the Paris agreement [2]. According to this agreement, global warming must be limited to 2 degrees (if possible, below 1.5 degrees) compared to the pre-industrialised level. The Paris agreement is ratified by 195 countries [3]. In addition to this global agreement, there are international strategies such as the European Green Deal [4] or national plans to ensure the fulfilment of the Paris agreement. However, national plans are often criticised by NGOs for being too vague, for lacking concrete measures and funding as well as for being too unambitious (e.g. [5–7]).

Complete decarbonisation requires a major transformation of the energy system. In 2019, about 77% of EU-wide GHG emissions were caused by the energy system[3] (including the combustion of fuels and fugitive emission from fuels [4]) [8]. Agriculture (11%) and industrial processes (9%) rank second and third. In the energy sector, about 85% of GHG emissions are caused by road transportation (28%), public electricity and heat production (26%), manufacturing industries and construction (15%), residential sector (11%), and commercial/institutional sector (4%) [8]. This distribution shows that all subsectors must be taken into account for achieving comprehensive decarbonisation of the overall energy system.

The high GHG emissions in the energy system are caused by the extensive use of fossil fuels. In 2019, 80.9% of the worldwide total primary energy supply was provided by coal, oil, and natural gas [9]. By comparison, in 1971, the share of fossil fuels was 86.6% [9]. However, between 1971 and 2019, the total primary energy consumption increased from 63 to

[1] strong reduction of GHG emissions; global CO_2 emission neutrality 2075; from 2075 onwards, more CO_2 is extracted from the atmosphere than emitted

[2] decreasing global CO_2 emissions from 2050 onwards; until then roughly constant

[3] In the report, it is defined as CRF Sector 1 Energy [8].

[4] By definition, the CRF Sector 1 Energy also includes CO_2 transport and storage. However, this data is currently only reported by Finland [8].

168 PWh/a [9]. Thus, during this period, the actual annual use of fossil fuels increased by nearly 81 PWh.

Cullen [10] summarised a relationship between population, GDP per population, energy per GDP and carbon per energy (eq. 1). For the energy system, the simplification to CO_2 emissions instead of considering all GHG emissions is acceptable, since about 96% of all GHG emissions can be attributed to CO_2 emissions [8].

$$Carbon = Population \cdot \frac{GDP}{Population} \cdot \frac{Energy}{GDP} \cdot \frac{Carbon}{Energy} \qquad (1)$$

This correlation can be used to explain the enormous increase in energy consumption between 1971 and 2019. In this period, the global population rose from 3.8 to 7.7 billion people (+104%) [11] and the global GDP increased by approx. 327% (inflation corrected) [12].

To reduce CO_2 emissions from the energy system three options are available: reduction in GDP, decrease of energy consumption per GDP or lowering CO_2 emissions of the energy supply. While the first option (a reduction in global GDP) can be ruled out politically and socially, the other two options are promising. Decrease of energy consumption per GDP refers to sufficiency or energy efficiency measures, while the last option (lowering CO_2 emissions of the energy supply) refers to decarbonisation. Finally, three possibilities for reducing CO_2 emissions in the energy system can be deducted therefrom [13]:

1. Sufficiency can decrease energy consumption based on behavioural changes such as changes in modal split or eating habits. In this context, social aspects such as acceptability, transparency and fairness must be considered in detail, especially from a global perspective.
2. Energy efficiency aims to the optimal use of energy by avoiding losses. Thereby, the entire energy system must be considered since the overall efficiency depends on the entire energy conversion chain. Furthermore, this also includes the utilisation of waste heat.
3. Decarbonisation of the energy system by substituting fossil energy sources with renewable ones. Such a transition affects the entire energy system, as the most promising renewable sources (e.g. photovoltaics, wind power) can only provide volatile electricity. However, our current energy systems are not designed for this. Accordingly, major changes to the entire energy system must be implemented. As an alternative, decarbonisation may also be achieved, if the CO_2 emissions of fossil fuels are captured and stored.

It is expected that all three possibilities need to be combined to meet the Paris agreement. Consequently, all of them are addressed in three peer-reviewed journal articles published by the author. These three articles are the core of this doctoral thesis. The knowledge gained from this doctoral thesis may help policy makers implement focused measures towards the full decarbonisation of their national energy system.

First, in chapter 2 relevant background information for this thesis is introduced. Afterwards, in chapter 3, the open research questions for this thesis were presented. Then, in chapter 4, results from the three peer-reviewed articles are compiled and discussed for answering the research questions. Chapter 5 concludes the entire thesis for policy makers. Finally, a scientific outlook is given in chapter 6.

The appendix consists of all publications this thesis is based on. Appendix A: Peer-Reviewed Publications includes all three peer-reviewed journal articles in full length. Further publications are shown in Appendix B: Further Scientific Publications.

2 CONTEXT

To improve any energy system in a target-oriented way, it is essential to clearly define and understand the structure, terminology, and boundaries of the system. In addition, the present situation and the latest research should also be included. This enables the efficient identification of open research topics and ensures relevance. Moreover, each improvement process requires an assessment criterion. This assessment criterion defines the direction of improvement (e.g. increasing energy efficiency or decreasing costs) and can be used to determine the overall degree of national energy system improvement.

2.1 Energy Conversion Chain and National Energy Systems

The energy conversion chain describes all the relevant steps between natural energy resources and the provision of energy services to meet human needs. At the beginning of this chain are national resources (e.g. coal in the ground). A resource is called primary energy, after making it usable (e.g. via coal mining). The usability of primary energy can be increased by various conversions (e.g. power plants). The output of such conversion units is defined as secondary energy (e.g. electricity). If necessary, several conversion units can be used in a sequence. Then, primary or secondary energy is transported to the final consumer. After deducting the transport losses that occur thereby, it is termed final energy (e.g. electricity that is actually delivered to the final consumer). In final energy applications, final energy is converted into useful energy (e.g. light, heat or mechanical work) to cover a required energy service (e.g. illuminated, comfortably warmed room). Energy services are so-called passive systems since they have no usable form of energy output [10]. Accordingly, passive systems represent the last step in the entire energy conversion chain.

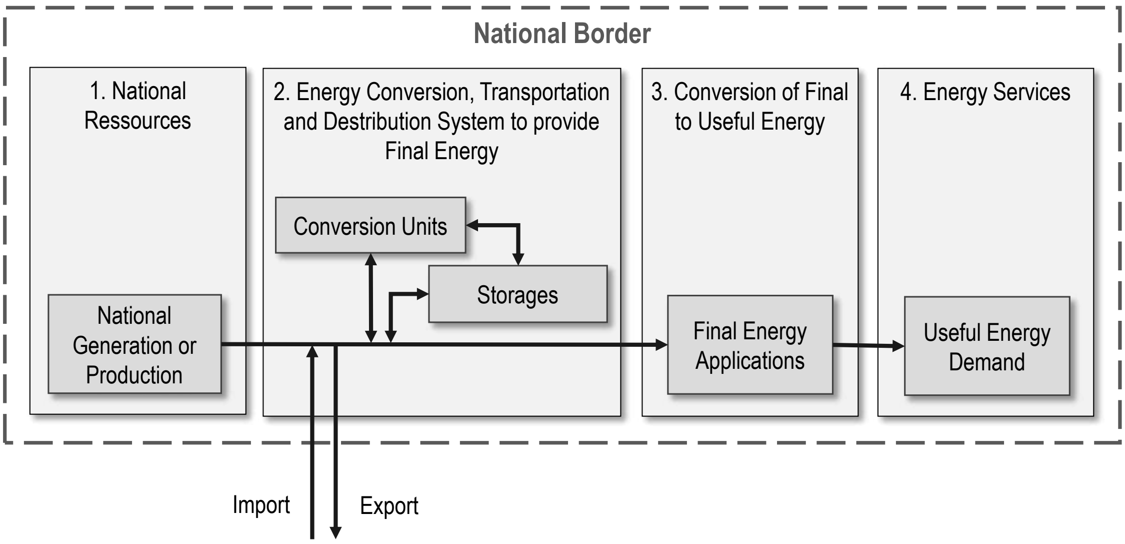

Figure 1. System boundaries of a national energy system

A national energy system covers the entire energy conversion chain within a country. Thereby, to provide meaningful results both is crucial a clear definition of the system boundaries and the method of energy accounting. Throughout the entire thesis, international definitions for energy balancing have been used (e.g. from IEA or Eurostat). In the following, important information for energy accounting and then the system boundaries are presented.

In this thesis, the national energy system is divided into four blocks (Figure 1). All four blocks are located entirely within the national border. The national energy system takes into account all energy flows and losses within the national border. Energy flows across the national border are interpreted as imports and exports. Import and export of primary, as well as of secondary energy, is considered. In this context, it is important to note that conversion and transport losses incurred abroad for the provision of secondary energy are ignored. However, this is in line with the IEA guidelines [14], since losses have to be allocated to the country in which they occur.

The national energy system (Figure 1) covers the entire energy conversion chain from resources (block 1) to energy services (block 4). The national resources in block 1 can be either fossil or renewable energy sources. Fluctuating electricity generation (i.e. generation from wind power, hydropower and photovoltaics) is a subset of renewable energy sources. Fossil energy sources always provide primary energy (e.g. coal or natural gas). In contrast, according to IEA, renewable energy sources can provide both primary energy (e.g. woody biomass) and secondary energy (e.g. electricity from wind or photovoltaic systems) [15]. However, renewable energy sources that provide secondary energy (according to IEA) are in fact only conversion units. For example, a photovoltaic system converts solar radiation (primary energy) into electricity (secondary energy) via the photoelectric effect. According to the guidelines, in such cases, the amount of secondary energy (e.g. electricity) is included in primary energy consumption or gross inland consumption but without considering the conversion losses (e.g. solar radiation to electricity) [15].

Block 2 represents the energy conversion, transportation and distribution system. It must compensate any differences in time, space and energy carrier between the energy sources and the final energy applications. To enable this, block 2 includes various conversion units (e.g. power plants or electrolysis), storage for various energy carriers (e.g. batteries, pumped storage power plants, gas storage) and energy grids (e.g. electrical or natural gas transmission and distribution grids, district heating grids). Block 2 includes both public and industrial energy systems. The final energy provided by block 2 is then converted into useful energy in final energy applications (block 3). The provision of useful energy can be achieved by different final energy applications. Finally, the useful energy satisfies the demand for energy services (block 4).

Blocks 3 and 4 represent the energy consumers, consisting of final energy applications as well as the demand for energy services. Final energy applications convert final energy into useful energy. The energy services apply the useful energy to satisfy human needs. They are called passive systems (according to [10]) and represent the end of the entire energy conversion chain. Accordingly, energy services have no useful energy or exergy output. The need for energy services can be subdivided into different economic sectors and useful energy categories. A distinction is made between the following economic sectors: industry, commercial and public services, residential sector, agriculture, and transport [16]. Furthermore, a variety of useful energy categories can be assigned to these economic sectors, representing the different forms of energy being required in the energy services, e.g. heat demand at different temperature levels, demand for lighting or ICT, mechanical work demand from stationary engines, demand for land transport or aviation [17]. Depending on the individual final energy application, the required final energy must be provided by different energy carriers.

As mentioned in the last few paragraphs, a national energy system must handle a variety of energy carriers and energy forms to fulfil all required energy services. Energy systems with various interacting energy carrier are called multi-energy systems (MES) [18]. According to Mancarella [18], MES have the following key roles: increase conversion efficiency and flexibility of energy systems as well as to find the optimal combination of centralised and decentralised resources. Pfenninger [19] states that optimisation of MES models can provide an in-depth understanding of the energy systems.

Real national energy systems are based on spatial constraints and operation is affected by temporal fluctuations of both energy supply and demand. In a first approximation, the spatial constraints are mainly relevant for the design and operation of energy grids. Temporal fluctuations are in particular relevant for the electrical energy system since generation and demand must always be balanced to avoid grid frequency instability. Furthermore, large quantities of electrical energy are more difficult and more expensive to store than chemical or thermal energy. Accordingly, for national energy systems, temporal differences between electricity generation and electricity demand must be considered in detail. For this purpose, residual loads of the electrical energy system are suitable. A residual load P_{RL} is defined by non-controllable demand $P_{Load,NC}$ minus the non-controllable generation $P_{Gen,NC}$ (eq. 2).

$$P_{RL} = P_{Load,NC} - P_{Gen,NC} \tag{2}$$

Positive or negative residual loads indicate situations in which the non-controllable generation is smaller/larger than the non-controllable demand, respectively. Residual loads can be compensated by the operation of controllable consumers (e.g. pumping operation of pumped storage power plants) or controllable generation units (e.g. power plants). Residual loads can be analysed using the discrete Fourier transformation (DFT). The DFT allows the transformation of any periodic signal from the time domain to the frequency domain [20]. According to the DFT analysis of the residual load, a national energy system with a high share of fluctuating electricity generation has seasonal, weekly, and daily flexibility demand [21] (Figure 2).

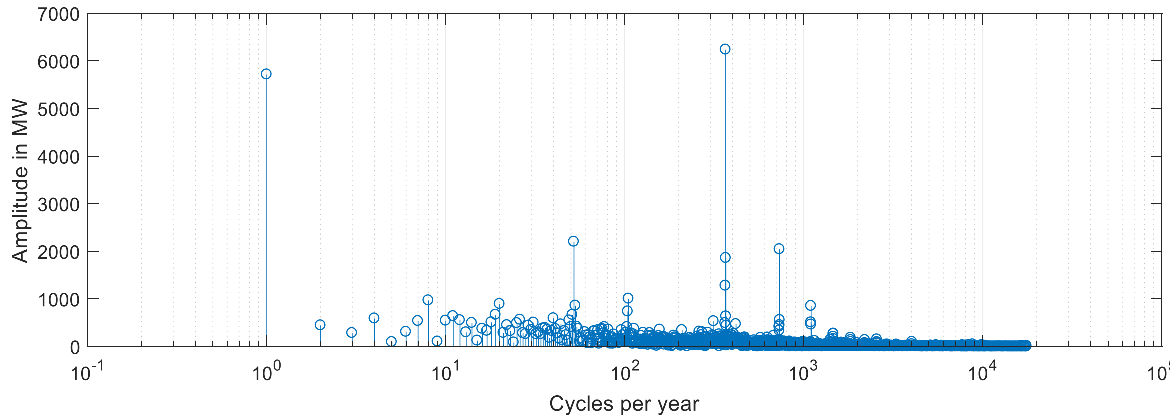

Figure 2. DFT analysis of a possible Austrian residual load with a very high share of fluctuating renewable generation. High amplitudes occur at one, 52 and 365 cycles per year as well as at the corresponding harmonics.

2.2 Austria Energy System

According to Statistics Austria [16], Austria had a primary energy consumption of 378.8 TWh in 2019. In addition, 25.1 TWh were used for non-energy purposes (mainly to produce chemical products). In total, this resulted in a gross inland consumption (GIC) of 403.9 TWh. Austria's GIC has increased by 38% from 1990 to 2019. However, the major increase occurred before 2005. Since 2005, the GIC has only risen by about 1%. A subdivision of the current GIC into the final energy consumption of the economic sectors and other relevant categories as well as the difference in relation between 1990 and 2005 is shown in Table 1. Of all final energy categories, consumption of transport has increased the most. Only the conversion losses and the final energy consumption of agriculture have decreased since 1990.

In 2019, 71% of gross inland consumption was still covered by fossil energy (Figure 3). Thereby, the largest share of fossil energy can be attributed to crude oil and its products (151 TWh) as well as to natural gas (119 TWh) [16]. More than 94% of fossil energy is provided by imports [16]. This combination of the high demand for fossil energy and a very high share of import leads to significant dependence on other countries and the world market. The use of renewable energies (including waste) is based almost exclusively on national potentials. The majority is attributable to the use of biomass (64 TWh) as well as to the fluctuating electricity generation (wind power, hydropower and photovoltaics, in total 49 TWh) [16]. About 40 TWh of the fluctuating electricity generation is generated by hydropower plants. Solar thermal and geothermal energy currently provide only a very small amount of energy.

Table 1. Breakdown of gross inland consumption in 2019 and difference compared to 1990 and 2005 (data source: [16])

Description	Consumption 2019 in TWh/a	Difference in relation to 1990 in %	Difference in relation to 2005 in %
Final energy consumption of industry	86.5	+46%	+3%
Final energy consumption of transport	114.6	+98%	+9%
Final energy consumption of residential sector	78.0	+15%	+2%
Final energy consumption of agriculture	6.1	-1%	-10%
Final energy consumption of commercial and public services	31.0	+55%	-11%
Transport losses [1]	7.0	+63%	+9%
Conversion losses [2]	23.3	-22%	-29%
Energy sector use [3]	32.1	+14%	-8%
Non-energy use [4]	25.1	+40%	+35%

[1] Considers losses of electrical and district heating grids
[2] Includes only national conversion losses of the energy conversion, transportation and distribution system (Block 2 in Figure 1), but not the conversion losses of the final energy applications.
[3] Describes the energy consumption required for enabling energy provisions or energy conversions (e.g. electricity for the circulation pump of a district heating grid, electrical own consumption of a power plant). However, about 78% of this consumption is caused by the blast furnace and the coke oven, which can be directly linked to the iron and steel industry.
[4] Energy carriers used as raw materials in production processes. Examples are the production of plastics from oil or ammonia and urea from natural gas.

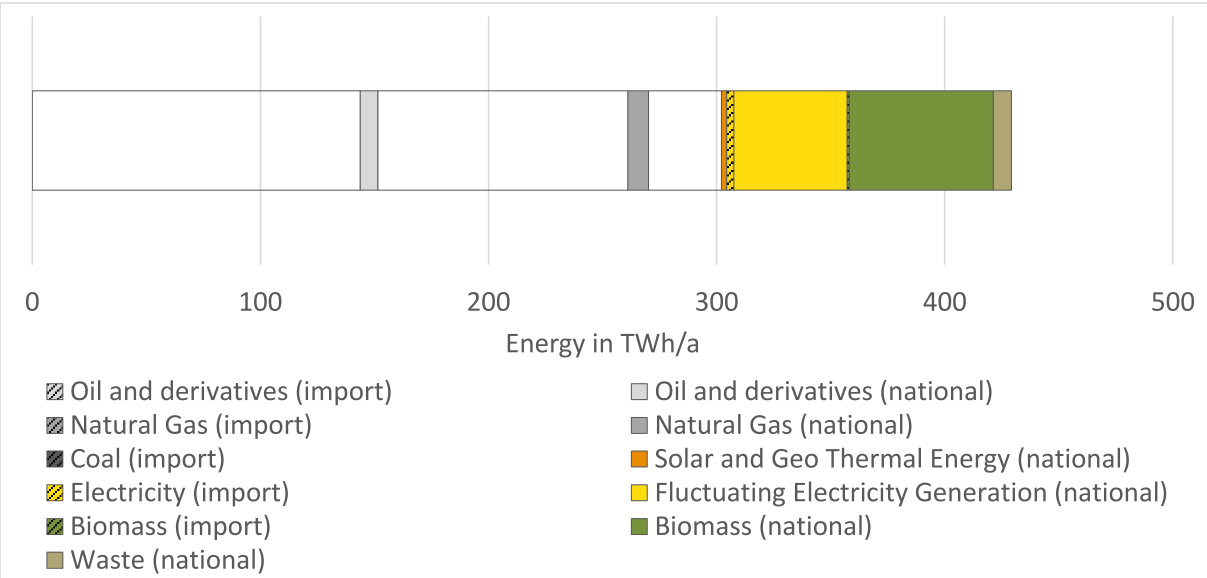

Figure 3. Austrian energy supply in 2019 (data source: [16])

The energy required to cover the gross inland consumption includes primary energy, secondary energy from renewable sources as well as from imports, following the IEA guidelines. The difference between the gross inland consumption in the first paragraph of this section and Figure 3 can be explained by the utilization of seasonal storages, e.g. for natural gas.

2.3 Energy Transition in Austria

As described in the previous section, about 71% of the total energy demand is currently covered by fossil fuels. Nevertheless, the current Austrian government program [22] aims for complete decarbonisation by 2040. However, there is currently no comprehensive strategy for how this goal is to be achieved. The integrated national energy and climate plan for Austria (according to EU Regulation 2018/1999 [23]) only covers the period from 2021 to 2030 [24]. This climate plan has the goal of reducing greenhouse gas (GHG) emissions (non-ETS) by 36% by 2030 compared to 2005. Various measures such as regulatory legislation, tax adjustments, infrastructure expansion, improving awareness, or subsidies are planned to reach this goal. The climate plan is only a domestic declaration of intent, but it is binding for the EU. Due to the lack of a comprehensive decarbonisation strategy for the period from 2030 to 2040, various studies, reports and initiatives are gathering knowledge to plan and implement the transformation. In the following, the most important ones are presented.

The Environment Agency Austria (EAA) publishes future energy and GHG emission scenarios every two years to fulfil the reporting obligations under EU regulation No. 525/2013 [25] (monitoring mechanism). These scenarios [26] describe possible developments of Austria's GHG emissions based on different assumptions. The most important scenario assumptions can be classified as WEM (with existing measures) to analyse the impact of implemented measures and WAM (with additional measures) to analyse the impact of already planned measures. In addition, the consequences of high-level political decisions are also analysed in separate scenarios, e.g. corresponding to electric self-sufficiency in 2030 or to the Paris agreement (COP21). All scenarios take into account the entire Austrian energy system, including all economic sectors, the entire energy conversion chain from primary to final energy with all losses as well as consumption of the energy sector and non-energy consumption.

The study "Energieautarkie für Österreich 2050" by Streicher et al. [27] examined how Austria could become energetically self-sufficient by 2050. For this purpose, the demand of every economic sectors was considered. In addition, the total renewable potential of Austria was calculated. By matching demand and potential, measures were identified which might be necessary to achieve the target. The study shows the importance of behavioural changes as well as of significant efficiency improvements in all areas. In total, a reduction in final energy demand between 40 and 50% is required. Furthermore, renewable generation must be massively expanded, between +85 and +131 TWh/a.

As part of the modelling region NEFI (New Energy for Industry), NEFI_Lab is developing three scenarios for the decarbonisation of industry [28]. These scenarios take into account all industrial subsectors. The business-as-usual scenario describes the trend based on currently available and already implemented measures. In contrast, the "Pathway of Industry" scenario determines the CO_2 and energy savings resulting from the measures and technologies envisaged by the industry itself. For this purpose, many industrial stakeholders are involved through interviews. The most ambitious zero-emission scenario aims for complete decarbonisation by 2050. To ensure this, backcasting is used to identify the necessary actions to achieve the target. For this scenario, a combination of technical considerations, scientific work and intensive stakeholder discussions is used to reflect industries' assessment of current policies and developments and provide the basis to bridge the gap towards complete decarbonisation. These scenarios are still being worked on and there are no final results published yet.

Besides this work, the project *Renewables4Industry* considered the entire industrial energy consumption (incl. consumption for industrial energy conversions such as for blast furnace and basic oxygen furnace). It turns out that the nation-wide renewable electricity potential would be needed almost entirely to supply industry [21]. In contrast, the study *IndustRiES* only included the industrial final energy consumption, except for the iron and steel sector. Nevertheless, they identified a large national supply gap of 71 to 94 TWh/a when taking into account all other economic sectors [29].

Baumann et al. [30] determined the Austrian demand for renewables gases in 2040. The demand of industry (incl. non-energy demand and sector energy use), power plants and transport (incl. e-fuels production) were included. In total, a demand between 89 and 138 TWh/a was identified and compared to the national potential of renewable methane (20 TWh/a). Accordingly, the future import of renewable gases is crucial. Besides the analysis of the future demand and potential for renewable gases, other studies examined the future demand and national renewable potential of electricity (e.g. [31,32]).

Abart-Heriszt et al. [33] published the final energy consumption per municipality and economic sector in Austria. Since all of the data is available online on their project website "energiemosaik.at" [34], it provides a valuable data basis for further studies. The study RegioEnergy [35] determined spatially resolved the potential of renewable for Austria.

In another publication by Gutschi et al. [36] the exergy efficiency of the entire Austrian energy system was analysed. One of the central findings is the extensive exergy destruction when using heating oil or natural gas for space heating. More efficient is the provision of space heating from co-generation via district heating or heat pumps. Apart from the provision of space heating and the use of CHP systems, no suggestions for improvement are identified in this study.

All these studies, as well as many others not mentioned in this thesis, already cover a wide field of research towards full decarbonisation of Austria. However, there are still issues open that are important for achieving this goal.

2.4 Exergy as Assessment Criterion

For the analysis of MES (and thus national energy systems), the selection of an appropriate assessment criterion is crucial [37]. Often used assessment criteria focus on economics, environment or energy [37]. Seldomly, exergy is used. For this thesis, exergy is chosen as an assessment criterion. Exergy as an assessment criterion focuses exclusively on technical aspects. In contrast to energy, it is based on the second law of thermodynamics and describes the actual working capacity of energy. Moreover, it enables the comparability of different forms of energy.

2.4.1 Fundamentals of Exergy

Calculations based on energy only have to comply with the first law of thermodynamics: the conservation of energy. Energy can never be created or destroyed, only converted. However, the physical properties of energy cannot fully describe the actual capacity to perform work. For example, one kWh of electricity has many more possible applications than one kWh of heat at 60°C. In 1956, Rant Z. introduced the physical quantity exergy to describe the actual working capacity of energy [38].

Thermodynamic systems always aim for the state of maximum equilibrium (maximum entropy). Deviations from equilibrium represent a difference in potential between a system and its environment. This potential difference can be used to perform work. Accordingly, this difference is called exergy and is defined by the actual state of a system and its environment.

In principle, energy En consists of two parts, exergy Ex and anergy An (eq. 3). The sum of anergy and exergy is always constant (conservation of energy). As mentioned before, exergy is the part of the energy that can perform work by using the deviation of the system to the environment. Eq. 4 defines the internal exergy of a closed system via the difference in internal energy U, in volume V times environment pressure p_0 as well as in entropy S multiplied by environment temperature T_0 compared to the system's environment (system itself is indicated without any index; environment is indicated using index 0). In this equation, kinetic, potential, nuclear exergy is neglected.

$$En = Ex + An \quad (3)$$

$$Ex = (U - U_0) + p_0 \cdot (V - V_0) - T_0 \cdot (S - S_0) \quad (4)$$

Anergy is already completely in equilibrium with the environment and cannot be used any further. In technical processes, the exergy of one energy carrier can be converted into the exergy of another energy carrier. Thereby, exergy is destroyed since entropy S_{gen} is generated due to irreversibilities (eq. 5). Exergy can always only be transferred from a higher to a lower exergy level.

$$Ex_{Dest} = T_0 \cdot S_{gen} \quad (5)$$

For technical applications, a distinction must be made between three forms of exergy, depending on the energy carrier. Exergy of thermal energy Q is defined by the temperature of the medium T and the environment T_0 (eq. 6). Mechanical or electrical energy is technical work W_t and consists therefore entirely of exergy (eq. 7). Exergy of chemical energy represents the deviation of the chemical composition to the standard environment [39]. Equation 8 shows the chemical exergy per mole of a gas mixture, using the universal gas constant $\bar{R}$. Mole fraction of gas k in the mixture at enter and environmental state is x_k and x_k^e, respectively. If a chemical reaction takes place in addition to the mixture, the Gibbs free energy ΔG of the reaction must also be included.

$$Ex = \left(1 - \frac{T_0}{T}\right) \cdot Q \quad (6)$$

$$Ex = W_t \quad (7)$$

$$Ex = -\bar{R} \cdot T_0 \cdot \sum_k x_k \ln\left(\frac{x_k^e}{x_k}\right) \quad (8)$$

The exergy reduction of a technical process is the difference between total exergy input and total exergy output. It can be classified into two categories: exergy destruction and exergy losses. As mentioned before, exergy destruction is caused by the entropy generation due to internal irreversibilities (eq. 5). Thereby, exergy is converted to anergy (e.g. conversion of fuel to heat since the amount of exergy in fuel is about 100% while in thermal energy is <<100%[5]). Exergy in unused energy output flows to the environment (e.g. unused waste heat in exhaust gas) are known as exergy losses. Understanding the cause of the exergy reduction enables deeper process insights that are not achievable using a solely energy-based approach (Figure

[5] Amount of exergy in thermal energy depends on the temperature (eq. 6). 100% can only be reached at an environmental temperature of 0 K or infinite high temperature of the medium.

4). These insights can be used for systematic improvements. In the following subsection, the exergy analysis of national energy systems is discussed in detail.

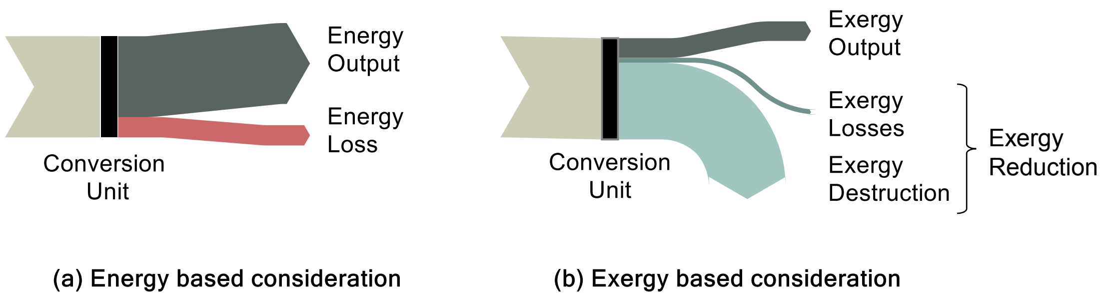

Figure 4. Comparison of energy and exergy losses of a generic conversion unit

2.4.2 Exergy Analysis of National Energy System

Efficiencies are important performance indicators for assessing and comparing processes or technologies. Energy or exergy reduction between input and output of a process are related to process' energy or exergy efficiency. High/low efficiency occurs at low/high reduction, respectively. The energy efficiency $\boldsymbol{\eta_{En}}$ or the exergy efficiency $\boldsymbol{\eta_{Ex}}$ are defined by the energy or exergy ratio of output to input. However, a huge difference between energy and exergy efficiency can occur: While different technologies might have comparable high energy efficiency, their exergy efficiency can vary strongly. Accordingly, considering energy efficiency exclusively is not sufficient in these cases. To calculate the exergy efficiency, only the energy efficiency as well as the relative exergy content $\boldsymbol{f_{Ex}}$ of all energy flows are required (eq. 9 to 11, nomenclature in Table 2). Therefore, exergy efficiency is not an alternative to energy efficiency. Instead, it is an extension to consider additional aspects.

Table 2. Nomenclature of the variables used for determining energy and exergy efficiency

Symbol	Explanation
Ex	Exergy
En	Energy
f_{Ex}	Exergy content
En_{Input}	Energy input
$f_{Ex,Input}$	Exergy content of energy input
En_{Output}	Energy output
$f_{Ex,Output}$	Exergy content of energy output
η_{En}	Energy efficiency
η_{Ex}	Exergy efficiency

$$\eta_{En} = \frac{En_{Output}}{En_{Input}} \quad 9$$

$$Ex = En \cdot f_{Ex} \quad 10$$

$$\eta_{Ex} = \frac{Ex_{Output}}{Ex_{Input}} = \frac{En_{Output}}{En_{Input}} \cdot \frac{f_{Ex,Output}}{f_{Ex,Input}} = \eta_{En} \cdot \frac{f_{Ex,Output}}{f_{Ex,Input}} \quad 11$$

Exergy efficiency can help to choose the technology which requires the least amount of actual working capacity to cover a specific demand. This is especially relevant for thermal applications, as heat's exergy content depends on the temperature level. Since an exergy content of 100% is only possible for thermal energy at infinitely high temperatures or by using an environmental temperature of 0 K, thermal energy always has a relevant share of anergy. For covering a thermal energy demand via a real process, the supplying energy needs a higher exergy content than the demand. An example of the exergy reduction of two different process technologies for heat supply is shown in Figure 5. Technology A represents a district heating grid while technology B corresponds to a gas boiler. The sum of anergy and exergy is energy. Both technologies have the same energy efficiency and consequently the same energy losses. The significant difference in the exergy content of the two inputs results in varying exergy reductions. However, in this example, only the energy losses and exergy reduction of the final energy application are considered.

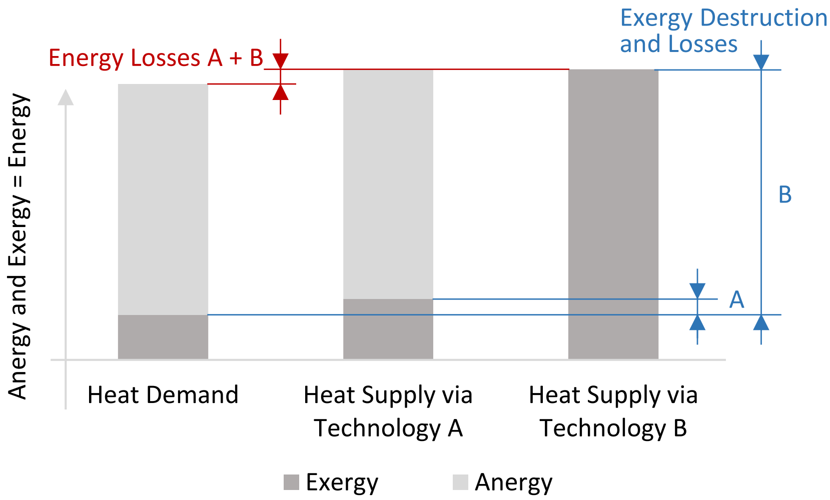

Figure 5. Comparison of energy losses (in red) as well as exergy destruction/exergy losses (in blue) for two different heating concepts (A and B). The sum of anergy and exergy is energy.

As mentioned above, exergy reduction is the sum of exergy destruction plus exergy losses. The determination of exergy destruction and exergy losses per process or unit is often referred to as exergy analysis. In the following, the calculation and its relation to the energy losses are presented.

Exergy losses are defined by the energy losses and their exergy content (eq. 13). Most energy losses are direct heat losses (waste heat losses such as thermal energy in the flue gas) or indirect heat losses (energy losses that cause heating, such as friction or electrical resistance). In both cases, the exergy content of energy losses can be calculated by the temperature of the media that dissipates the heat (e.g. flue gas or air). Besides heat losses, other energy losses might be a leaking gas with potential energy (e.g. compressed air) or chemical energy (e.g. methane). Exergy losses still have work capacity (i.e. could be used to perform work) but this is currently not being used. For example, the thermal energy in the flue gas of an industrial plant causes exergy losses since the thermal energy in the flue gas has an exergy content bigger than 0. These exergy losses could be reduced by implementing a waste heat recovery system. Thereby, exergy that would otherwise be dissipated to the environment can be used to cover a thermal energy service.

Exergy destruction can be determined by the exergy balance. It is defined as the sum of all exergy inputs minus the sum of all exergy outputs minus the sum of all exergy losses (eq. 14). In detail, it can be calculated from all mass transferred into or out of the system, their exergy contents as well as all energy flows into or out of the system which are not connected to a mass transfer (heat exchange, mechanical work) (eq. 15). Exergy destruction is to be understood as a loss of the ability to perform work while the amount of energy stays the same. To reduce exergy destruction, the most important thing is to minimise the difference between the exergy content of the main energy input and the main energy output. An example of massive exergy destruction is the provision of thermal energy for space heating through the incineration of chemical energy. Chemical energy has an exergy content of about 100%, while low-temperature heat has a very low one (e.g. heat at 60°C has about 15%). Low-temperature heat can only be used for thermal applications [6] which require even lower temperatures. In contrast, chemical energy can be used for various tasks such as generating electricity or in internal combustion engines. The nomenclature of this equation set is shown in Table 3.

$$\sum_i En_{In,i} = \sum_i En_{Out,i} + \sum_i En_{Loss,i} \tag{12}$$

$$Ex_{Losses} = \sum_i En_{Loss,i} \cdot f_{Ex,Loss,i} \tag{13}$$

$$Ex_{Dest} = \sum_i Ex_{In,i} - \sum_i Ex_{Out,i} - Ex_{Losses} \tag{14}$$

[6] From a theoretical point of view, even low-temperature heat can be used for generating electricity in a thermal power plant. However, the efficiency is so low that it has no practical relevance.

$$Ex_{Dest} = \underbrace{\sum_i Q_i \cdot f_{Ex,Q,i}}_{\substack{\text{Heat Exchange} \\ \text{(without mass transfer)}}} + \underbrace{\sum_i W_i}_{\substack{\text{Work Exchange} \\ \text{(without mass transfer)}}} + \underbrace{\sum_i M_{In,i} \cdot f_{Ex,In,i} - \sum_i M_{Out,i} \cdot f_{Ex,Out,i} - \sum_i M_{Loss,i} \cdot f_{Ex,Loss,i}}_{\substack{\text{Exergy of all mass transfers (including all types of exergy} \\ \text{such as chemical, potential, kinetic or thermal exergy} \\ \text{but only related to mass transfer)}}} \quad (15)$$

Table 3. Nomenclature of the variables used for determining exergy losses and exergy destruction

Symbol	Explanation
$En_{In,i}$	Energy input i
$En_{Out,i}$	Energy output i
$En_{Loss,i}$	Energy loss i
$f_{Ex,*,i}$	Exergy content of corresponding energy of mass i
$Ex_{In,i}$	Exergy input i
$Ex_{Out,i}$	Exergy output i
Ex_{Losses}	Total exergy losses
Ex_{Dest}	Total exergy destruction
$M_{In,i}$	Mass input i
$M_{Out,i}$	Mass output i
$M_{Loss,i}$	Mass loss i
Q_i	Thermal energy i into or out of the system without mass transfer, e.g. via radiation
W_i	Work performed to or from the system without mass transfer, e.g. via mechanical movement

Exergy analysis of national energy systems requires the consideration of all conversions from resource to energy service [37]. Thereby, for each conversion unit, an exergy analysis can be carried out as mentioned above. The final conversion step is the provision of useful exergy to fulfil a required energy service. By adding up both the exergy destruction and exergy losses of all conversion units in the entire conversion chain, the total exergy footprint of the energy service can be determined. An example of exergy destruction and exergy losses for an entire conversion chain as well as the total exergy footprint is shown in Figure 6 and Figure 7.

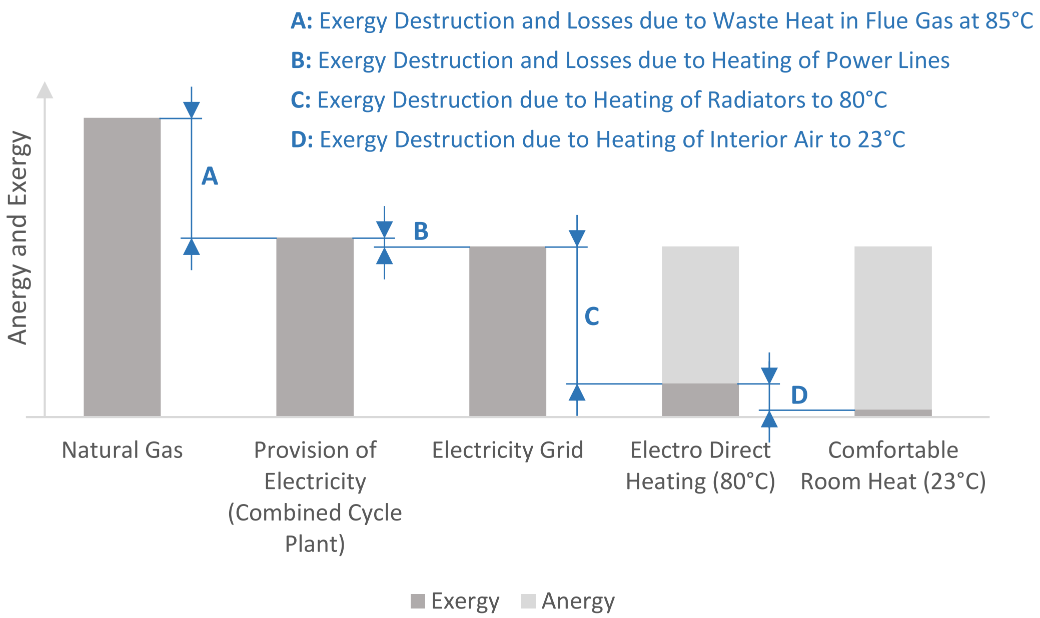

Figure 6. Example of exergy and anergy as well as exergy destruction and exergy losses from resource to energy service

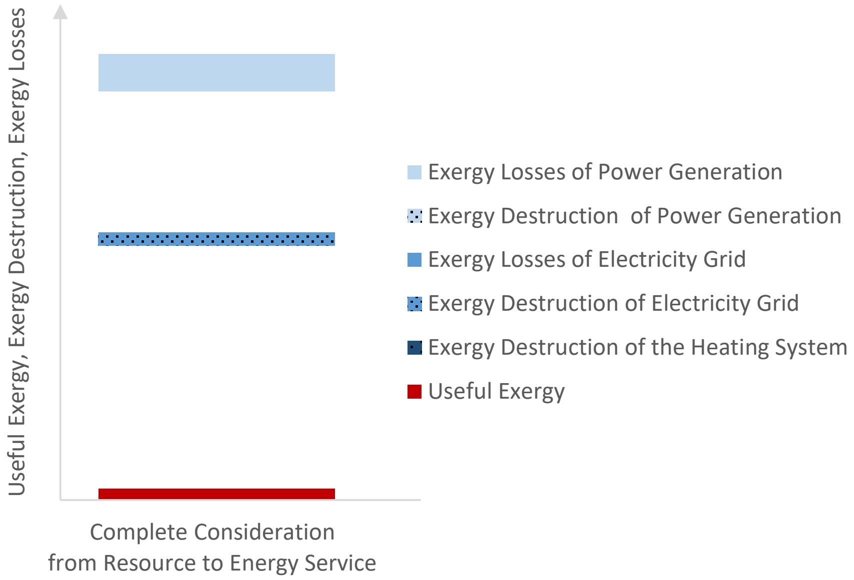

Figure 7. Example of useful exergy (red), exergy destruction (dotted) and exergy losses (single coloured) from resource to energy service.

If several possible energy conversion chains are available to fulfil an energy service, the most efficient one can be selected based on the total exergy footprint. Alternatively, the most relevant conversions to be improved can be determined for a defined energy conversion chain. Exergy losses can be reduced by decreasing energy losses, e.g. via increasing process efficiency or via implementing waste heat recovery. Increasing the energy efficiency of one process also reduces exergy destruction. The implementation of waste heat recovery usually leads to higher destruction since flue gas temperature decreases. However, the reduction in exergy losses exceeds the additional exergy destruction. Accordingly, both energy efficiency and waste heat recovery decrease overall exergy reduction. To reduce exergy destruction further, the difference in exergy content between the main input and the main output should be as small as possible. In most cases, this is only possible by switching technologies (e.g. using district heating instead of a gas boiler).

2.4.3 Exergy Efficiency as Design Parameter

In this subsection, the differences and advantages of exergy efficiency as a design parameter compared to energy efficiency are identified. Here, the focus is on mathematical optimisation. Energy efficiency as an assessment criterion minimises energy losses. In contrast, in this thesis, maximising exergy efficiency is achieved by minimising the sum of exergy destruction and exergy losses. In other words, exergy reduction is minimised, regardless of the ratio between exergy destruction and exergy losses. In general, neither an exclusively energy-based nor an exergy-based approach is better. It depends on the individual task.

To determine the difference between both assessment criteria, possible changes in the energy balance (eq. 12) as well as in the exergy balance (eq. 14) must be analysed. All possible changes in these two balances can be attributed to three cases: changing energy efficiency, changing exergy content of energy losses as well as changing exergy content of energy input and energy output.

Changing energy efficiency: Any change in energy input, losses and output affect the energy efficiency directly. A measure to increase energy efficiency leads to a reduction in total energy input for the same total energy output and thus to reduced energy losses (eq. 12) [7]. Due to the linear correlations between energy and exergy, the increased energy efficiency results in decreased exergy inputs and exergy losses (eq. 10 and 13). The change in total exergy reduction Ex_{Red} is proportional to the change in energy inputs (eq. 16, derived from eq. 14). Consequently, energy efficiency measures are taken into account in both assessment criteria, no difference can be obtained.

$$Ex_{Red} = Ex_{Dest} + \sum_i En_{Loss,i} \cdot f_{Ex,Loss,i} = \sum_i En_{In,i} \cdot f_{Ex,In,i} - \sum_i En_{Out,i} \cdot f_{Ex,Out,i} \qquad 16$$

Changing exergy content of energy losses: A real-world example of this is the reduction of the flue gas temperature by mixing it with ambient air to simplify gas cleaning. However, in the case of implementing a waste heat recovery in the future, the energy loss must have a sufficient exergy content. Regardless of such a variation, energy inputs, energy outputs and

[7] For simplicity, only a decrease in energy input due to an increase in energy efficiency is discussed here. These assumptions are without limitation of generality - changing them to energy output and/or decreases in efficiency leads to the same statements.

their exergy contents remain unchanged. According to equation 16, the total exergy reduction Ex_{Red} will not change (right side of the equation stays exactly the same). As a consequence, changes in the exergy content of the energy losses only leads to a shift between exergy destruction and exergy losses and no difference between both assessment criteria can be identified.

Changing exergy content of energy input and energy output: For the total exergy reduction, only the gap in exergy content between input and output is relevant, as long as all energy values are constant (eq. 16). If the exergy content of the output of a conversion unit has a higher value than actually required, the reduction to the actual required exergy content is shifted to a subsequent energy conversion unit.

Example: A district heating system is supplied by a natural gas-fired boiler (f_{Ex} = 100%[8]). If the network is operated with a flow temperature of 120°C (f_{Ex} = 28%) instead of the minimum required 80°C (f_{Ex} = 20%), the total exergy reduction in the heat supply decreases (eq. 16). However, only heating water at 65°C (f_{Ex} = 16%) is required for the consumers. Thus, in both cases a total exergy reduction from 100% to 16% takes place, the cases only differ in the location of the exergy reduction (changes in energy losses and exergy losses are neglected).

Therefore, the minimal exergy content of the output is always defined by the application, technology or process chain (e.g. minimum required temperature). Since a higher exergy content of the output just shifts the location of the exergy reduction, the total exergy reduction can only be lowered by reducing the exergy content of the energy input (if all energy values are constant).

In the last example, a geothermal energy source (100°C, f_{Ex} = 24%, same energy efficiency as the gas boiler) could significantly reduce the total exergy reduction, as only a gap from 24% (geothermal energy) over 20% (flow temperature of the district heating grid) to 16% (consumer demand) instead of from 100% (natural gas) to 16% (consumer demand) would occur.

This shows the only actual discrepancy between the two assessment criteria: An exclusively energy-based criterion cannot distinguish different types of energy sources unless there is an advantage in energy efficiency. In the previous example, from an energy-based point of view, the natural gas boiler and the geothermal source leads to equivalent solutions. In contrast, an exergy efficiency criterion takes energy efficiency into account and can include the exergy contents of all energy carriers purposefully. Thus, in this example, an exergy-based assessment criterion would select geothermal energy.

[8] Exergy content of chemical energy is not exactly 100% but it is a sufficient simplification

Furthermore, the exergy efficiency enables a trade-off between the use of low exergy energy carriers and their energy efficiency. This means, to minimise exergy reduction, reduced energy efficiency might be acceptable if a low exergy energy carrier can be used instead. In the last example, if the gas boiler has a higher energy efficiency than the geothermal source, it would be selected by an energy-based assessment criterium. However, the use of geothermal energy still results in an overall higher exergy efficiency and would be chosen by an exergy-based approach.

Exergy as an assessment criterion also has three additional advantages:

- The analysis of exergy destruction and exergy losses can enable deeper insights into the entire energy system such as the location and cause of the exergy reduction. By identifying the location of the greatest exergy reduction, target-oriented action such as focused research and implementing design and operational improvement can be initiated.
- The exergy content of energy carriers enables elegant comparability of supply. This means it can be used to determine which energy flow is suitable for meeting a demand regardless of the energy carrier
- Adaptations of exergy and its accounting enable the inclusion of additional aspects, e.g. by using cumulative exergy consumption (CExC) [40]. CExC allows the exergy expenditures of technology construction and implementation or the exergy expenditures outside the system boundaries to be considered.

3 RESEARCH OBJECTIVES AND METHODOLOGY

A large number of publications regarding the decarbonisation of the Austrian energy system already cover a wide field (section 2.3). However, the knowledge base is not yet fully comprehensive. Besides others, two aspects that have not been analysed before, neither nationally nor internationally, were identified:

- In principle, energy efficiency improvements are highly recommended by many parties such as the government, scientists, or other experts. However, the optimal mix of technology for energy conversion units and final energy applications of an entire energy system to maximise overall energy efficiency has not yet been investigated. Such an analysis would be necessary for providing accurate recommendations and can support policy makers to ensure measures towards overall energy efficiency with the highest impact.
- Renewable gases, especially hydrogen, is currently a subject of political discussion. However, the future total demand for renewable gases, the national green hydrogen potential, as well as the national hydrogen production costs have not yet been analysed. However, these facts are essential for a well-founded discussion. Furthermore, these results could be an important basis for policy makers' decisions.

To profoundly perform these two open research tasks, the entire national energy system (including all economic sectors, the entire energy transition chain from resource to energy service as well as all losses and demands) must be considered. Otherwise, interactions between technologies, potentials and demands might not be comprehensively included, or double accounting might occur. In the following, the research questions to address these two aspects are defined.

3.1 Research Objectives

As mentioned in the last section, this doctoral thesis analysis two recent aspects of the Austrian energy system, relevant for national decarbonisation. Since these two open aspects have not yet been answered internationally, this thesis is also important for the scientific community. Based on these two aspects, three blocks of research questions have been identified (enumeration below). The first block addresses the current situation of Austria, as it is the common basis for both aspects. Then, blocks two and three deal with the first and the second aspect, respectively. Due to the novelty of the thesis, the research questions contain both, conceptional/general questions as well as specific questions about the decarbonisation of Austria. However, by applying the methodology to other data, all research questions with a focus on Austria can also be answered for any other country/region.

1. **Determining the current demand for energy services:**
    - How can the demand for energy services be identified?
    - How much work is required for fulfilling all current energy services in Austria and where is it located spatially and sectorally?
2. **Covering the demand for energy services:**
    - How do conversion units and final energy applications interrelate for maximum exergy efficiency? How can this be determined?
    - What technology mix of conversion units and finale energy applications could maximise national overall exergy efficiency?
    - In contrast to the current supply in Austria, how much exergy could be saved nationally by the implementation of the optimal technology mix?
    - How large are the renewable potentials and would self-sufficiency be theoretically possible?
3. **Future energy supply and import needs:**
    - How can the effect of technology-related measures or behavioural changes be investigated and what impact will they have on the energy supply in the future?
    - Which share of the total renewable gas demand can be covered nationally?
    - What are the costs for imported and nationally produced green hydrogen?

To answer all these research questions, the Austria energy system is analysed. Thereby all economic sectors, all useful energy categories, all relevant energy flows, all losses, as well as the entire energy conversion chain from resource to energy service are considered (section 2.1 and 2.2). A detailed description of the methodology is presented in the following section.

3.2 Methodology

This thesis is based on three peer-reviewed journal articles that address all presented research questions. Figure 8 shows the most important relations between the articles and the research question blocks. In this section, the methodical approach of answering all blocks of research questions is briefly described. More details about the individual methodologies can be found in Appendix A: Peer-Reviewed Publications.

To answer the first block of research questions, a comprehensive data basis on the current situation in Austria is required. For this purpose, an exergy analysis of the entire current Austrian energy system was carried out including all economic sectors, all forms of useful energy, all types of energy flows and all relevant energy carriers. This is exclusively based on publicly available data, publications, and statistics. The novelty is the spatially resolved combination of many different data sources. Thereby, high quality was achieved by combining top-down and bottom-up approaches. The exergy assessment of the useful energy demand was identified as a reasonable concept for describing the demand for energy services (subsection 4.1). This novel approach enables an energy form-independent identification of the energy services according to their theoretical minimum required technical work. All details are published in the first journal article ([41]).

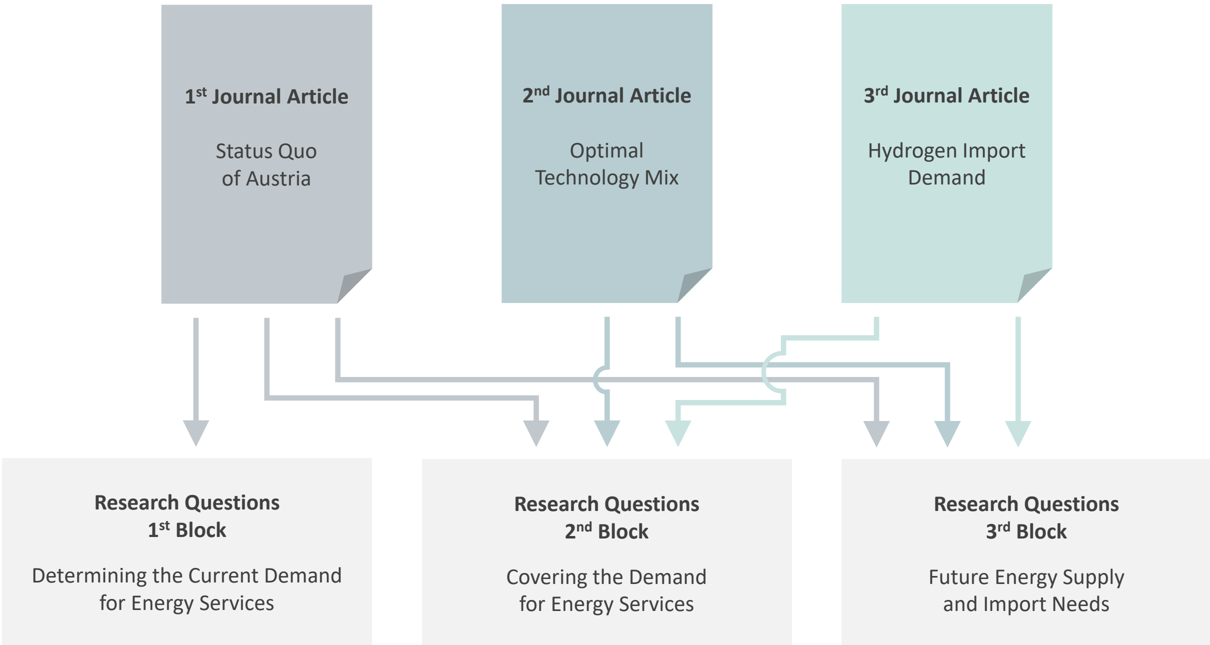

Figure 8: Main connection between the three journal articles and the three blocks of research questions

The second block of research questions about the interrelations between conversion units of the energy conversion, transportation and distribution system as well as of final energy applications was addressed by using an optimisation model based on linear programming. This optimisation model covers the entire Austrian energy system (Figure 1) and includes an objective function that ensures the maximisation of the overall exergy efficiency. To maximise overall energy efficiency, over 100 technologies for both energy conversion, transportation and distribution system as well as final energy applications are available for selection, sizing and operation. To determine the interrelations, the results of the optimisation were analysed for different boundary conditions (e.g. variation of the available potential of renewable generation or of efficiencies). By using all currently required energy services of Austria (first block of research questions) as boundary conditions the optimal technology mix for maximising overall exergy efficiency as well as the overall minimal required exergy can be identified. This optimisation model and its application to the Austrian energy system was firstly published in the second journal article ([42]) and further developed within the third journal article ([43]).

To answer the other research questions of the second block, results of the comprehensive exergy analysis (used to answer the first block) are required: information on how the current demand for energy service is currently covered and how much exergy is currently required for this. The difference between current and minimal required exergy determines the possible exergy savings. In addition, the technical potential of all renewable energy sources in Austria was determined to enable statements of national self-sufficiency. The renewable potential was also determined spatially resolved based on top-down and bottom-up approaches with the exclusive use of publicly available publications and statistics. The spatially resolved exergy analysis as well as the technical potential of renewable energy sources were published in the first journal article ([41]).

A scenario analysis for 2030, 2040 and 2050 was performed to address the third block of research questions. Two scenarios were investigated with regard to the development of the Austrian energy system in terms of energy consumption, self-generation and self-production as well as import demand. The first scenario is based on the optimisation model from the second journal article. It ensures maximal efficiency through optimal technologies but does not include any behavioural changes. In contrast, the second scenario includes extensive behavioural changes but uses only conventional technologies. Demand was based on the first journal article. Extensive renewable expansion till 2050 is assumed for both scenarios. The expansion results in negative residual loads (eq. 2), which are used for determining the national green hydrogen potential. The economic share of the green hydrogen potential was calculated through a cost analysis and the import demand identified. This scenario analysis was published in the third journal article ([43]) and answers the third block or research questions entirely.

In addition to the three main publications, conference papers, contributions to journal articles of colleagues and scientific reports were also published. Some of these publications were published as the lead author, others as a co-author. However, all these publications provided an important basis for answering the three blocks of research questions. The publications were dealing with spatially resolved renewable potential and demand (first and second block of research questions, publications: [21,44]), potential and demand of renewable gases (second and third block of research questions, publications: [30,45–48]), energy grids (second block of research questions, publications: [49,50]), as well as one about the discrete Fourier transform (second block of research questions, publication: [51]).

3.3 Contribution to the Scientific Knowledge

This thesis contributes to scientific knowledge on two levels. On the one hand, a novel combination of approaches and methods are presented. These new combinations can be further developed or applied to other applications such as other countries or regions. On the other hand, these novel combinations allow the determination of results, relevant for the decarbonisation of Austria as well as of other countries with similar structures. Furthermore, the findings can be used as a basis for further research.

Until now, no comprehensive energy or exergy data set for Austria were published. This thesis includes, specially resolved, the current primary exergy consumption, the current useful exergy demand as well as the technical potential of renewable energy sources (included: woody biomass, biomethane, biodiesel, ethanol fuel, photovoltaic, wind power and hydropower). This data enables the first spatially resolved comparison of technical renewable potentials and primary exergy consumption or the current useful exergy demand. At the moment, only spatially resolved renewable potential studies (e.g. [35]) or final energy consumption (e.g. [33]) exist individually. The exclusive consideration of final energy is not sufficient since the rest of the process chain is neglected (e.g. conversion and transportation losses). A spatially resolved combination of primary energy consumption and renewable potentials is crucial for future energy infrastructure planning. Furthermore, the novel concept of current useful exergy demand describes the technology-independent need for energy services. In contrast to the useful energy demand, the useful exergy demand enables the comparison of different forms of energy (e.g. demand of shaft work or thermal energy) based on actual capacity to perform work. This is important when applying to an entire national energy system. All these results can be the basis for many further research projects. For example, the second and third articles were also based on the results of the first article. In addition, the Austria-wide current totals of potentials and demand are also of high relevance for policy makers. Thereby, consideration of the entire energy system and the use of exergy are important to enable comparability.

No study has been found that examines the optimal technology mix of an entire energy system (including both energy conversion, transportation and distribution system as well as including energy applications for all sectors) on a technical basis. All studies that take the entire energy system (all sectors, multiple energy carriers, final energy applications and the energy conversion, transportation and distribution system) into account are based on cost optimisation (e.g. [52–54]). In this thesis, the optimal technology mix was determined purely based on technical aspects. This optimal technology mix is an alternative to cost-driven aspects to generate exclusively technical and systemic knowledge. This is not only relevant for Austria but many findings can also be transferred to other countries. Furthermore, it can also serve as a basis for in-depth research into the further development of the relevant technologies. In addition to scientific research, the optimal technology mix is an important basis for policy makers to ensure the transformation of the national energy system towards decarbonisation and maximum efficiency.

In this thesis, the total national renewable gas demand, the national potential as well as the national import demand, could be identified for the first time. Thereby also economic aspects have been included. The potential of national green hydrogen was determined with the exclusive use of negative residual loads. Such an approach has already been used for two Italian case studies ([55,56]), but without considering the entire energy system. However, it is important to include the entire energy system since the decarbonisation strategy of each sector influences hydrogen demand and potential. All other studies found about decarbonising the entire energy system consider hydrogen but do not analyse hydrogen aspects (e.g. potential, demand, production cost) in-depth (e.g. [53,57,58]). In this work, both approaches are combined, addressing hydrogen aspects in detail but including the entire energy system. These meaningful results can be also applied to other countries with similar structures (e.g. other European countries). However, the differences between the respective country and Austria must be considered individually.

4 Results and Discussion

In this chapter, the results of all research questions (section 3.1) are presented and discussed. A more comprehensive description can be found in the individual journal papers in Appendix A: Peer-Reviewed Publications.

4.1 Current National Demand for Energy Services

In this section, the first block of research questions is answered. First, the determination of the demand for energy services is presented. Then, the demand is analysed in terms of economic sectors, useful energy category and spatiality.

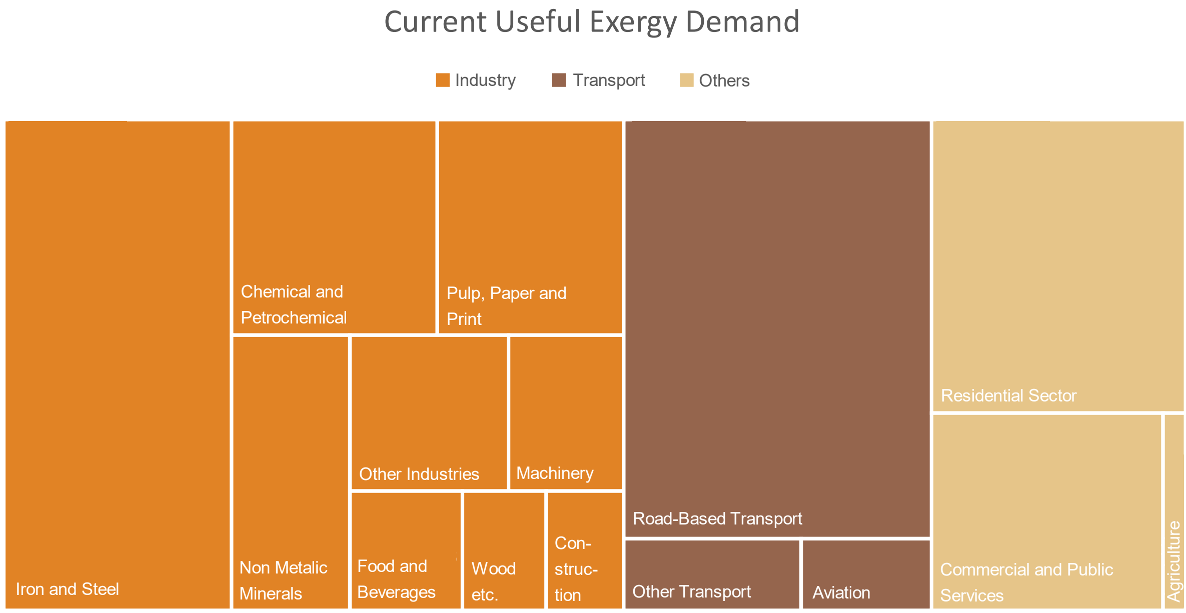

Figure 9. Breakdown of the current useful exergy demand (CUED) into different subsectors

In general, the national demand for energy services is based on the useful energy demand. However, the Austrian useful energy demand is not published. Instead, only the use of final energy per useful energy category[9] is provided by Statistics Austria [17]. The useful energy demand can be calculated from the final energy demand by using the efficiency of the final energy application. Since the useful energy analysis does not contain all required information (e.g. temperature levels), other data sources were included and combined with the data from Statistics Austria. Nevertheless, the useful energy demand of different useful energy categories may not be comparable, as the exergy content may be different (e.g. heat demand at 25°C or demand of shaft work). For this reason, the useful energy demand of each useful

[9] Space heating and air condition, vapor production, industrial furnaces, stationary engines, lighting and computing, electrochemical purposes, traction

energy category was multiplied by the respective exergy content to calculate the useful exergy demand. The useful exergy demand is the technology-independent theoretical minimum exergy demand to meet an energy service. The total nationwide sum expresses the minimum demand of exergy to meet all energy services of an entire country. However, this minimum exergy demand will always be exceeded since all technical applications are lossy and the entire conversion chain must be considered.

The current useful exergy demand (CUED) of all energy services in Austria is 133 TWh/a[10]. This demand can be allocated to industry (52%), transport (26%), residential sector (13%), commercial and public services (8%) and agriculture (1%). Almost two-thirds of the total industry demand (70 TWh/a) is caused by the three subsectors iron and steel (26 TWh/a), chemicals and petrochemicals (10 TWh/a), as well as pulp, paper and print (9 TWh/a). The demand in transport is predominantly allocable to road transport (30 TWh/a, 85%). A graphical representation of the share per sector and subsector is shown in Figure 9.

In addition, the assignment of the current useful exergy demand to the useful energy categories is important (Figure 10). Almost 96% of the useful exergy (133 TWh/a) is used to cover the demand for thermal energy (on different temperature levels) and for shaft work (stationary as well as movable such as cars). The total useful exergy for thermal applications (76 TWh/a) can be divided into the ranges up to 100°C (29%), between 100°C and 400°C (18%) and above 400°C (53%).

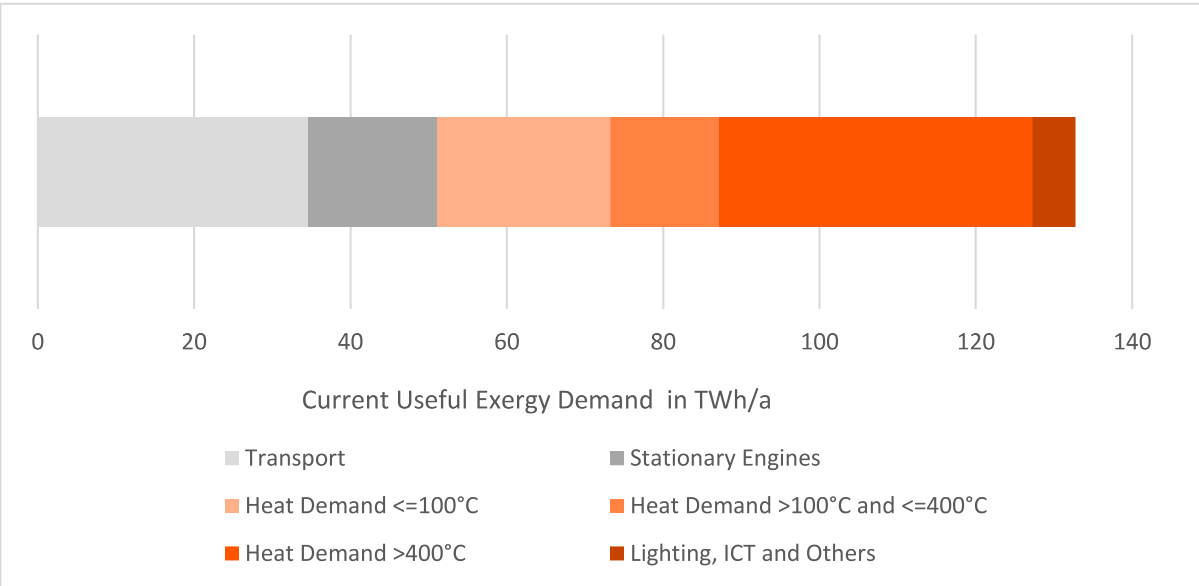

Figure 10. Current useful exergy demand (CUED) by useful energy categories.

[10] This value is slightly higher than the one published in the first peer-review article. This is caused by the usage of improved data sources in the second and third journal article.

In Austria, the current useful exergy demand is mainly located in metropolitan areas as well as industrial regions: all larger cities including the surrounding regions, the valley of Mur and Mürz in Styria, the Industrieviertel in lower Austria, the Danube region between Linz and Vienna as well as nearly entire rest of upper Austria. Besides these main regions, some individual districts also have a high demand due to industry (e.g. Kufstein or Wolfsberg). The highest demand per area has the districts of Linz (212 GWh/(km² · a)), Steyr (34 GWh/(km² · a)) and Vienna (26 GWh/(km² · a)). In contrast, the lowest demand per area have Murau (0.17 GWh/(km² · a)), Lienz (0.20 GWh/(km² · a)) and Hermagor (0.23 GWh/(km²*a)). These examples show how unevenly demand is located in Austria.

4.2 Covering the Current Demand for Energy Services

In this section, the research questions of the second block are addressed. First, the background, the interrelations between conversion units and final energy applications as well as the optimal technology mix are discussed. In the end, the achievable energy savings and the possibility of self-sufficiency are presented.

A holistic model is needed to comprehensively investigate the interrelations between conversion units of the energy conversion, transportation and distribution system and final energy applications. This model must take into account the entire national energy system (Figure 1). This includes all energy conversions, all exergy reductions, all economic sectors, all useful energy categories as well as all relevant energy carriers. This holistic model is necessary to cover all possible supply paths for covering all energy services. For example, if only the electric system were considered, a switch from battery electric vehicles (BEV) to fuel cell electric vehicles (FCEV) would result in a reduction in exergy consumption and in exergy reduction (less power plant capacity needed for electricity supply in winter). However, the additional exergy reduction due to the lower efficiency of the FCEV compared to BEV would not be taken into account. In addition, a holistic model prevents the same renewable potentials from being used more than once. Using the holistic model and suitable input data, mathematical minimisation of total exergy reduction provides the selection, sizing and operation of technologies that maximise overall exergy efficiency.

By using this holistic optimisation model to optimise different sets of input data, the interrelations between conversion units of the energy conversion, transportation and distribution system as well as the final energy applications can be systematically investigated. In this analysis, the renewable generation, the efficiencies of power plants and the possibilities for importing electricity were varied. This interrelation is especially relevant for switching between chemical energy-based and electrical final energy applications.

According to the analysis, to maximise overall energy efficiency, the decision for a technology switch from a conventional chemical energy-based final energy application to an electrical final energy application depends on two aspects. First, the difference in exergy efficiency of the final energy applications. Secondly, on the annual average efficiency of the electricity supply $AAESE$ (eq. 17 to 19). It can be calculated using the annual controllable electricity generation E_{ConGen} , annual volatile electricity generation E_{VolGen} , the annual volatile electricity import E_{VolImp} , as well as the average annual efficiency of the controllable electricity generation η_{ConGen}, and of the electricity transportation and distribution grid η_{Grid}. In addition, the relative annual share of controllable generation r_{ConGen} and volatile generation r_{VolGen} are relevant. A low annual efficiency of electricity supply (e.g. due to inefficient power plants without waste heat recovery or a low share of renewable generation) can prevent electrification. In these cases, electrification has a lower overall exergy efficiency than the conventional final application, supplied by renewable energy. For example, heat pumps for space heating in winter have a higher overall exergy efficiency than gas boilers even when a high share of electricity must be provided by gas-fired power plants. This can be explained by the high exergy efficiency of heat pumps.

$$r_{ConGen} = \frac{E_{ConGen}}{E_{VolGen} + E_{VolImp} + E_{ConGen}} \qquad 17$$

$$r_{VolGen} = 1 - r_{ConGen} \qquad 18$$

$$AAESE = (r_{ConGen} \cdot \eta_{ConGen} + r_{VolGen} \cdot 1) \cdot \eta_{Grid} \qquad 19$$

Technically, the exergy reduction for the provision of chemical energy (e.g. hydrogen or sustainable methane) must also be taken into account for both possible final energy applications. However, this is only relevant if a significant proportion of the chemical energy is produced nationally with exergy reduction (e.g. through electrolysis). According to section 2.1, energy losses and exergy losses has to be accounted at the country they occur. This means imported chemical energy has no national exergy reduction. Since in the second journal article the national electrolysis production was negligible, this aspect is not included in detail.

Next, the Grassmann diagram presenting the optimal technology mix for the Austrian energy system is shown in Figure 11. This figure shows the high relevance of renewable gases in an exergy optimal energy system: 52% of the primary energy or 42% of the final energy is covered by renewable gases. Besides renewable gases, also electricity is crucial for efficient energy systems: electrification of final energy applications increases by 44% compared to 2018 [16].

The determination of this exergy optimal technology mix (which results in the minimum achievable exergy consumption) considers one year in hourly values and includes all economic sectors and useful energy categories but excludes all spatial aspects. Consequently, different results may be obtained when including also local conditions. However, the following main findings for optimal technologies can be stated independently thereof:

- The thermal supply up to 150°C is based on extensive excess heat recovery and utilisation (including also low-temperature excess heat) as well as on intensive use of heat pumps. Thermal storage increases flexibility and allows the heat pumps to operate when negative residual loads occur. Heat demand at higher temperatures can be optimally covered by incineration of chemical energy carriers such as woody biomass (whenever possible), hydrogen or sustainable methane. Direct electric heat is never used, even with the most ambitious renewable expansion.
- Electric drives result in the highest efficiency for both stationary engines and mobile applications (e.g. overhead wiring, battery-electric drives). In case electric drives are not feasibly for mobile applications (e.g. due to required range or load) then fuel cell electric drives should be used to ensure maximum efficiency. E-fuels are not an alternative due to the long conversion chain and inefficient internal combustion engines. These are only reasonable in the absence of alternatives (e.g. for aircrafts).
- The difference in the seasonal component between renewable electricity generation and electricity consumption requires on one hand large controllable electricity generation capacities in winter. Extensive import of electricity and expansion of fluctuating electricity generation reduce the required capacity of power plants. On the other hand, in summer, negative residual loads can be used in electrolysis and central heat pumps for supplying district heating grids (thermal girds should include thermal storage for flexibility). In total, the amount of renewable gas required in winter exceeds production in summer many times over. In addition to flexibility for compensating the seasonal component, short-time flexibility (between minutes and a few days) is also required such as pumped storage or photovoltaic home storages. These short-time flexibility options should have a grid-serving operation.

In addition to the main findings independent of spatial aspects, there is also one result where a spatial analysis is necessary for recommendation: the gasification of woody biomass. To increase exergy efficiency, almost all woody biomass is converted to wood gas and used for covering thermal demand at high temperature levels. However, the gasification required huge infrastructure adaptions (plants, grids, storage, final energy applications).

As mentioned in the context, exergy reduction can be caused by exergy destruction and losses. About two-thirds of the entire exergy reduction (102 TWh) occurs in final energy applications, the rest in the energy conversion, transportation and distribution system. The share of exergy destruction in relation to the total exergy reduction is 90 or 83% for the energy conversion, transportation and distribution system or for the final energy applications, respectively. The low share of exergy losses is caused by the extensive excess heat recovery as well as direct and indirect electrification (excess heat at low temperatures).

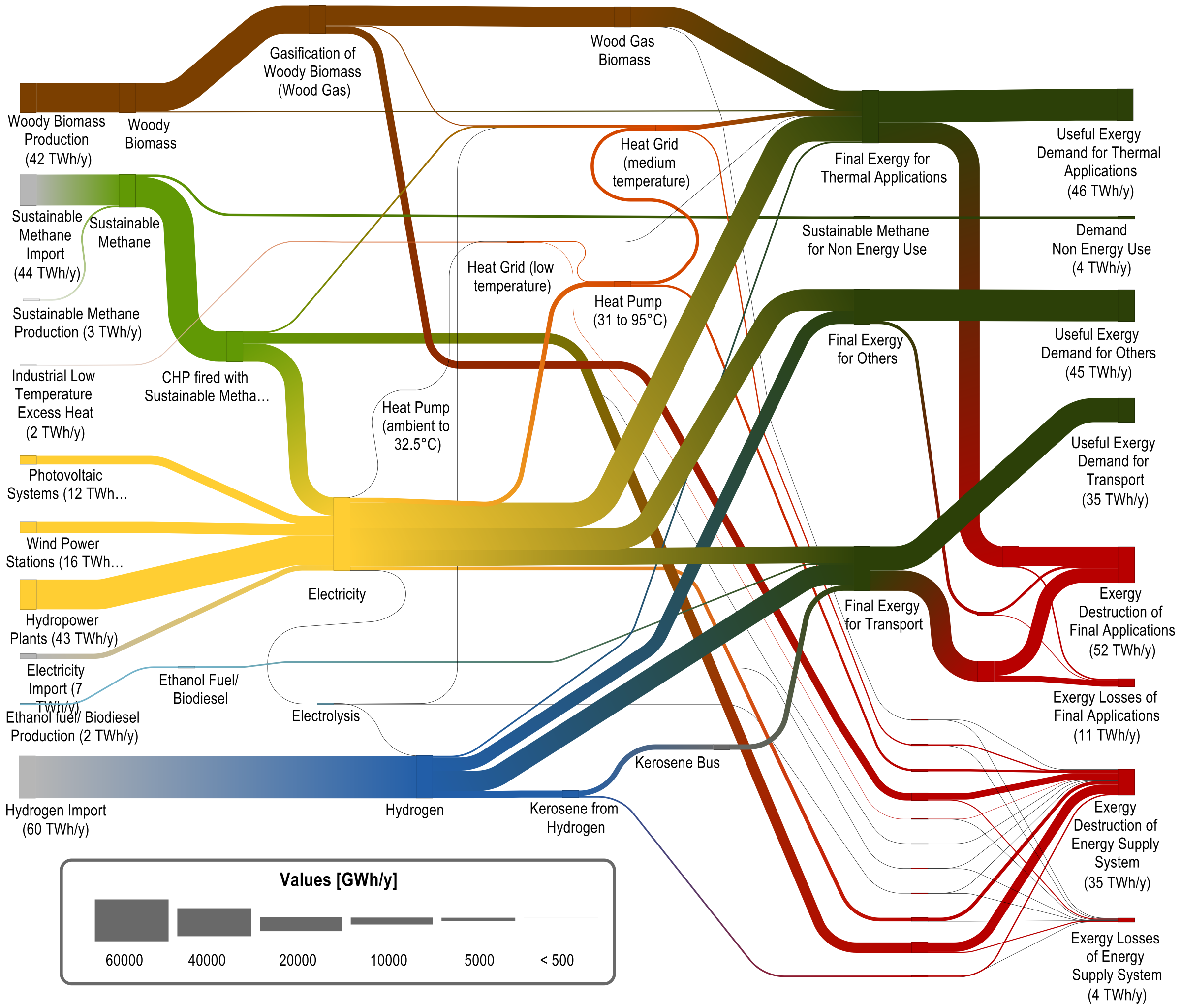

Figure 11. Grassmann diagram of the exergy optimal energy system

Finally, the question about possible overall exergy saving as well as about self-sufficiency is discussed. In Austria, currently, about 374 TWh of primary energy (370 TWh of primary exergy) are used to meet all national energy services (excluding non-energy use). This results in an exergy efficiency of about 36%[11]. All exergy analyses found of other countries are at least 15 years old. Most of them are lower but in the same order of magnitude. For example, the exergy efficiency of many other countries mainly in the 1980s and 1990s was between 13 and 30% [59]. For the year 2005, Gutschi et al. (2008) [36] identified an Austrian overall exergy efficiency of about 21%.

[11] This value is slightly higher than in the first peer-reviewed article. The difference is caused by a higher current useful exergy demand as mentioned in the previous footnote.

Although the current useful exergy demand shows significant differences between the main sectors (Figure 9), the primary exergy consumption required to cover the entire demand is rather evenly distributed to industry, transport and others (Figure 12). Even if all technical exergy potentials of renewable energy sources (RES) in Austria would be utilised, the current primary exergy consumption could not be covered. This lack of national renewable potentials also occurs in a purely energy-based approach. However, by using the most efficient technologies and the optimal combination of them throughout the entire energy system, primary exergy consumption could be significantly reduced. A primary exergy reduction of 142 TWh/a [12] (-38%) compared to the current exergy consumption would be possible. Thereby, the resulting minimal achievable primary exergy consumption still ensures the fulfilment of all current energy services. This reduction would increase the overall exergy efficiency to 58%[13] and would make national self-sufficiency theoretically possible.

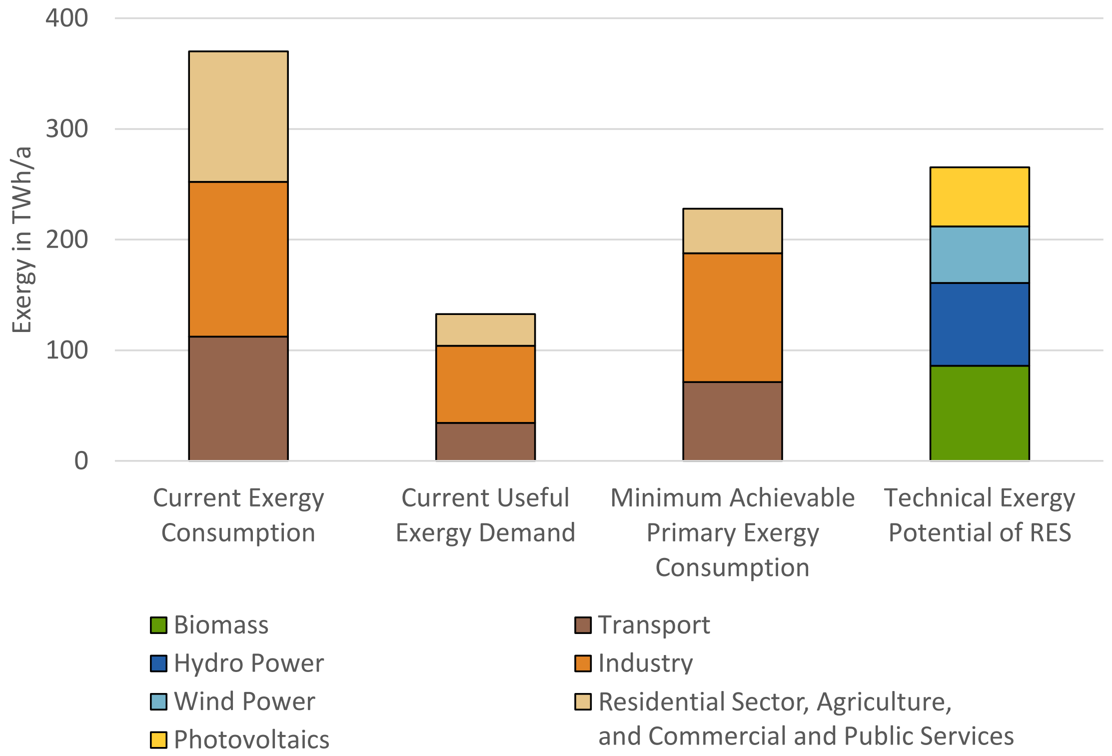

Figure 12. Comparison of the current exergy consumption, the current useful exergy demand, the minimal achievable primary exergy consumption by using only the most efficient technologies as well as all technical exergy potentials of renewable energy sources.

Austria's self-sufficiency would require major efforts, as the renewable potentials are distributed rather evenly over the entire area. The difference between the technical exergy

[12] This value is slightly different from the second peer-reviewed article. The deviation can be explained by not including non-energy use as well as using different processes for iron reduction due to consistency reasons.
[13] This value is slightly different from the value in the second peer-reviewed article. Same explanation as in the previous footnote.

potential of renewables and current exergy consumption per district is shown in Figure 13. In this figure, the colour scale ranges from beige (potentials exceed consumption) to white (potential and consumption about equal) to turquoise (consumption exceeds potentials). Extensive energy infrastructure would be necessary to transport the exergy from the sources to the centres of consumption. However, the actual feasibility and implementation of self-supply were not investigated in this thesis. The complete utilisation of all technical potentials seems unrealistic to the author.

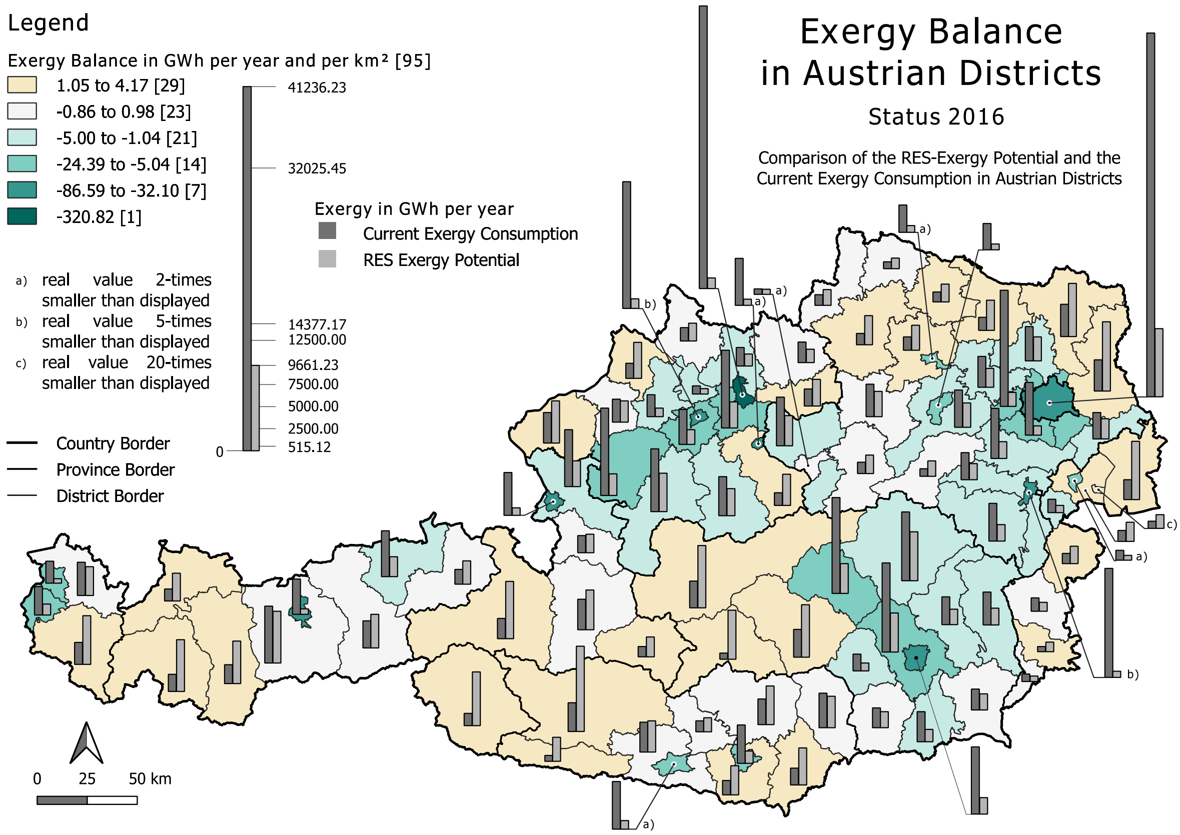

Figure 13. Comparison of total technical renewable potentials and current exergy consumption per district in Austria (map source: Statistics Austria - data.statistik.gv.at).

4.3 Future Energy Supply and Import Needs

A scenario analysis is chosen for analysing and comparing technology-based measures and behavioural changes for the reduction of the primary energy consumption in the future. This will answer the third block of research questions. In scenario analyses, it is important to clearly define the scenario assumptions to draw the right conclusions. This scenario analysis focuses on the years 2030, 2040 and 2050. To ensure comparability, both scenarios are fully decarbonised for each year and consider the same ambitious expansion of renewable energy sources. The aimed expansion of the current government program [22] for the period 2020 to 2030 will be continued linearly until 2050.

The first scenario *Energy Efficiency* is based on maximum exergy efficiency through the optimal mix of novel technologies. This scenario does not include any changes in behaviour. Here, the already explained exergy optimisation from the second block of research questions is applied. In contrast, the second scenario *Sufficiency* considers very strong behavioural changes of society but uses conventional technologies. To achieve fully decarbonisation, fossil energy sources are being substituted for renewable ones, such as natural gas being replaced by renewable gas or usage of e-fuels in road transport. It is important to note that according to the scenario assumptions, only renewable gas is imported and e-fuels are produced therefrom nationally. The assumptions according to the achievable behavioural changes are based on the scenario WAMplus published by Environment Agency Austria [60].

Both scenarios aim for full decarbonisation. Thus, the primary energy consumption is covered by electricity (fluctuating generation), biomass and waste, solar thermal energy as well as the import of renewable gases. The results indicate a decreasing primary energy consumption over time for both scenarios. The reduction is caused by the continuous increase in energy efficiency as well as the more extensive changes in behaviour. According to the scenarios, the primary energy consumption will be between 233 TWh/a (scenario *Energy Efficiency*) and 252 TWh/a (scenario *Sufficiency*) in 2050. For comparison, assuming the same economic and efficiency development but without any behavioural changes or changes in technologies, the Austrian primary energy consumption would decrease from currently 374 in 2018 to 371 TWh/a in 2050.

Despite the very different scenario assumptions: both scenarios have similar total electricity demand, especially in 2040 and 2050 (in 2030: 101 to 82 TWh/a; in 2040: 103 to 97 TWh/a; in 2050: 116 to 117 TWh/a; for all years, the former value represents scenario *Energy Efficiency*, the later scenario *Sufficiency*). The difference in 2030 is caused by the higher electrification rate in final energy applications in the scenario *Energy Efficiency.* Significantly larger quantities of electricity must be provided from controllable power plants as well as from imports. Due to the constant expansion of renewable generation less controllable generation is required towards 2050 and the difference becomes smaller (net non-fluctuating electricity provision in 2050: 1.9 TWh/a in scenario *Energy Efficiency*, 2.2 TWh/a in scenario *Sufficiency*). Electricity from volatile generation is used to provide hydrogen if it is not required for any other application.

Towards 2050, the total demand for renewable gases will decrease in both scenarios. It ranges between 128 TWh/a (in 2030) and 99 TWh/a (in 2050) for scenario *Energy Efficiency*. In contrast, for scenario *Sufficiency,* it will be between 195 TWh/a (in 2030) and 125 TWh/a (in 2050). This reduction can be explained by two previously mentioned aspects:

- Decreasing primary energy consumption according to scenario assumptions.

- Increasing fluctuating electricity generation (according to scenario assumption) decreases the positive residual loads in winter. Consequently, less renewable gas for firing controllable power plants is required.

The entire available amount of waste (between 7 and 9 TWh/a) and biodiesel/ethanol fuel (2 TWh/a for each year), as well as the complete potential of solar thermal energy (between 6 and 7 TWh/a) is used, regardless of the scenario and year. Furthermore, the exploited potential of sustainable methane (biomethane from biogas plants) is the same for both scenarios and increases from 8 TWh/a to 17 TWh/a The scenarios differ significant in the utilisation of woody biomass. In the scenario *Energy Efficiency,* renewable gas (wood gas) is provided via the gasification of woody biomass. Since gasification and methanation of woody biomass is a novel technology, is only available in this scenario. Gasification has a technical potential of 28 TWh/a wood gas (for each considered year). Due to the longer conversion chain, wood gas is never converted to methane. Instead, wood gas is directly used for thermal applications. In the other scenario, woody biomass is used in CHPs as well as for space heating. In the scenario *Energy Efficiency*, the entire available woody biomass is used for each year (42 TWh/a). In contrast, in the scenario *Sufficiency*, there is a slight import demand in 2030 (4 TWh/a). Behavioural changes lead to a decreasing demand over time. In 2040 or in 2050 there is a woody biomass surplus of 3 or 7 TWh/a.

The total technical import demand for renewable gases is the difference between the total demand for renewable gases and the technical potential of national renewable gases. In this thesis, the technical potential of national renewable gases is composed of technical green hydrogen potential, technical wood gas potential (already mentioned) and technical sustainable methane (already mentioned). The technical potential for the national production of green hydrogen is based on the negative residual loads and other controllable electricity consumers. For scenario *Energy efficiency* it increases from 0 TWh/a in 2030 to 14 TWh/a in 2050. In the other scenario, it starts at 7 TWh/a in 2030 and reaches 37 TWh/a in 2050. This huge difference between both scenarios is mainly caused by the higher electrification rate in scenario *Energy Efficiency.*

In 2030, the total technical import demand of renewable gases ranges between 92 TWh/a (scenario *Energy Efficiency*) and 180 TWh/a (scenario *Sufficiency*). Until 2050, it decreases to 40 TWh/a (scenario *Energy Efficiency*) and 72 TWh/a (scenario *Sufficiency*). At least 41% of the total renewable gas demand must be imported in 2050. All these values are presented in visual form (time-resolved and as annual total) in Figure 14.

These results can easily be transferred to a business-as-usual scenario[14]. Such a scenario is comparable to the scenario *Sufficiency* but with higher primary energy consumption as well as higher total demand of renewables gases since there are no behavioural effects. As a result, in 2050, the import demand would be significantly more than 72 TWh/a (value of scenario *Sufficiency* in 2050). As a rough estimate, the import demand would about the same as the total gas demand since in a business-as-usual scenario no significant expansion of natural sustainable methane or national green hydrogen production is assumed. Finally, the import demand of the business-as-usual scenario might be in the range between 210 and 250 TWh/a in 2050.

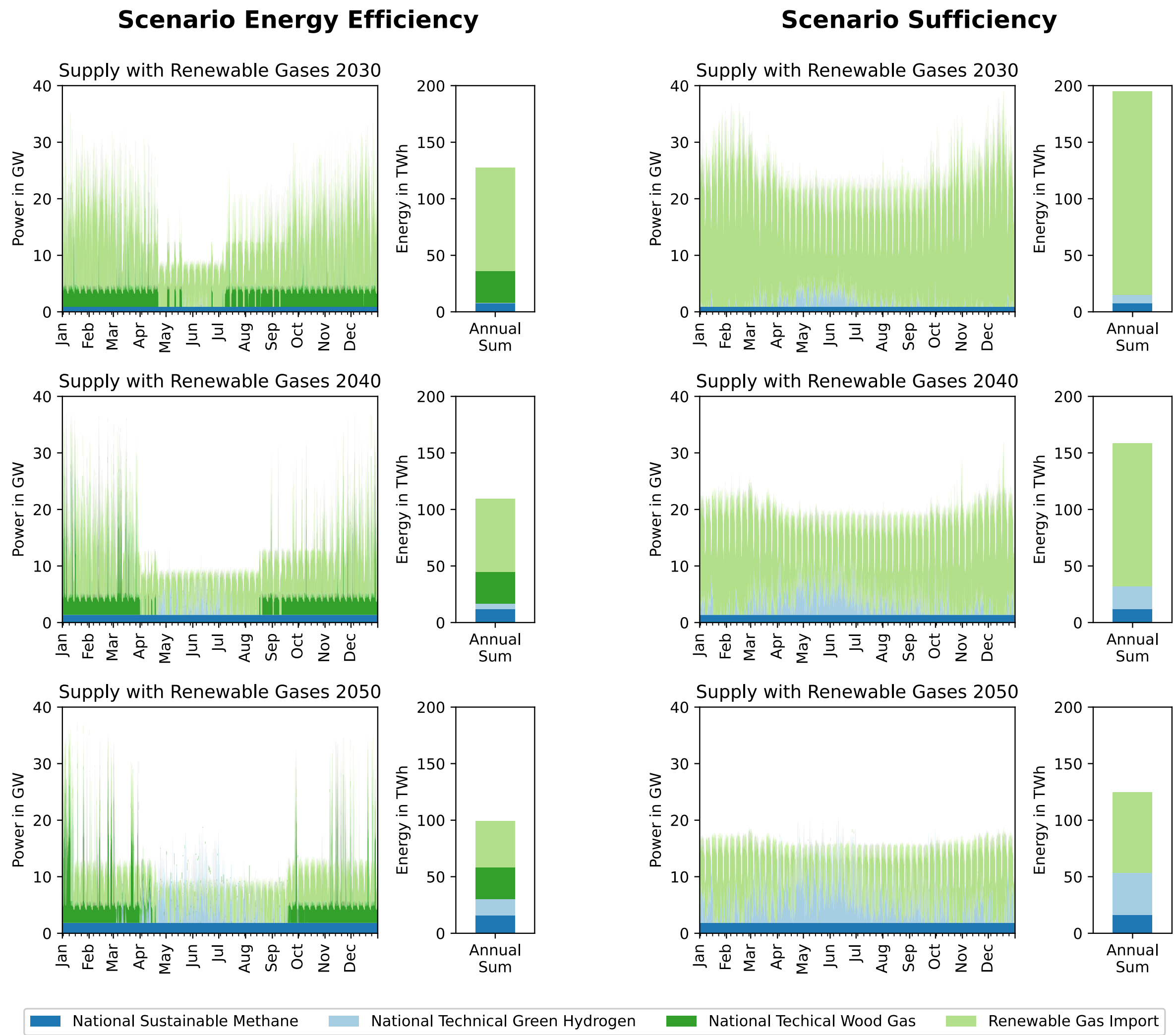

Figure 14. Technical supply of renewable gases for both scenarios and all considered years.

For the subsequent economic analysis regarding national green hydrogen production, only the sufficiency scenario was analysed in detail. In this economic analysis, the average levelized cost of hydrogen production was determined. To ensure economic feasibility, the minimum

[14] This also applies to other countries with similar structures to Austria.

full load hours were specified individually for each year. In addition, the necessary run-up curves were identified. It shows that the economic potential of green hydrogen is approximately 3 to 4 TWh/a lower than the technical potential, independent of the considered year. The average production costs of national green hydrogen are between 12.1 €ct/kWh$_{HHV}$ (in 2030) and 6.3 €ct/kWh$_{HHV}$ (in 2050). The reduction in costs can be attributed primarily to the increase in full-load hours (in 2030: 1953 h/a; in 2040: 2736 h/a; in 2050: 3000 h/a), which is the result of the continuous expansion of fluctuating renewables. In addition, technology learning curves leads to decreasing system costs over time.

The average production costs calculated for Austria are higher than the costs published in the literature for green hydrogen. The difference can be explained by the exclusive use of the negative residual load for green hydrogen production in this work. Other studies typically analyse renewable energy sources at optimal locations (e.g. offshore wind power in the North Sea, photovoltaics in North Africa, geothermal energy in Iceland) exclusively for electrolysis operation (e.g. [61]). However, transport costs must also be considered to ensure comparability. In principle, a distinction can be made between direct imports (liquefied via ships or compressed via pipelines) and indirect imports (chemically bound, e.g. as ammonia or methane) [62]. In 2050, transportation costs of hydrogen to Central/Western Europe may range between 2.1 €ct/kWh$_{HHV}$ (pipeline from best of Iberia) and 4.5 €ct/kWh$_{HHV}$ (via ship from Australia) [63]. In 2030, Hydrogen Council predicts about 3.1 €ct/kWh$_{HHV}$ for shipping liquid hydrogen from Arabian Peninsula to Europe [62]. Transportation costs for hydrogen chemical bound as ammonia will be between 1.7 and 2.1 €ct/kWh$_{HHV}$ in 2050 [63]. However, in the case of indirect imports, the additional costs and losses of conversion must also be considered. High transportation costs for direct imports result from the low energy density of hydrogen and the energy required for cooling in the case of liquid hydrogen [63]. To sum up, in the long term, the production costs of green hydrogen in optimal regions for renewable generation plus transportation costs may be comparable to national green hydrogen production using only negative residual loads in Austria. Nevertheless, this is only valid if the expansion of volatile electricity generation in Austria is massively expanded.

5 CONCLUSION

In this thesis, important aspects of the decarbonisation of the Austrian energy system are addressed. A comprehensive methodology was developed to answer the research question. The methodology consists of the following three main parts:

- The determination of Austria's status quo (first journal article) provides a extensive spatially resolved data basis (including both demand and renewable potentials), which was not available before. Central is the characterisation of the technology-independent demand for energy services as useful exergy. This is the basis for the entire thesis. Due to limitations in data availability (e.g. deviating available years, different data sources, non-existent data), there may be discrepancies when looking at details compared to the real world. However, these uncertainties are not relevant for high-level assessments and do not affect the conclusions of this thesis.
- The methodology in the second journal article provides the mix of conventional and novel technologies that maximise overall exergy efficiency. Thereby, the entire Austria energy system and the current demand of all energy services is considered. Due to the technical focus, all technical limitations (e.g. actual efficiencies) are considered but other (non-technical) aspects such as minimum full load hours of conversion units, investment costs, energy costs, changes of the passive systems, current infrastructure and possible transformation pathways or social aspects are excluded.
- The temporal development in the third journal article is based on a scenario analysis. For these scenarios, assumptions (e.g. trend in energy demand, trend in costs) about the future are made. One scenario describes the implementation of maximum exergy efficiency, while the other assumes very strong behavioural changes of society. Important: no scenario is intended to predict the future. However, knowledge about the future can be generated from a combined analysis of several scenarios.

In Austria, all technical potential of renewable energy sources cannot cover the current primary energy consumption. Moreover, the realisable renewable potentials will be less than the technical ones. Realisable potentials must include further aspects such as economy, social acceptancy, competition for land, competition for utilisation of resources, nature conservation or moment protection. All these additional aspects will limit the actual exploitable potential. Accordingly, national self-sufficiency is only possible if energy consumption can be reduced. A reduction in energy consumption can be achieved by sufficiency measures (e.g. changes in modal split), minimising demand of passive systems (e.g. thermal insulation or reduction of car weight) as well as measures to increase the energy efficiency (e.g. switching to most efficient final energy applications such as heat pumps for space heating).

The exergy analysis of the current Austrian energy system results in an overall exergy efficiency of only 36%. The implementation of the most exergy-efficient technology mix throughout the entire energy system could increase the exergy efficiency up to 58%. This corresponds to a primary exergy saving of 142 TWh/a (-38%) in relation to the current primary exergy consumption of Austria and requires no changes in behaviour. However, comparable savings are possible by using only conventional technologies combined with massive sufficiency measures.

Regardless of the type and extent of the reduction in primary energy consumption as well as the overall exergy efficiency, decarbonised Austria will be mainly supplied with electricity and renewable gases (or other chemical energy) in future. However, biomethane from biogas plants and gasification as well as hydrogen from fluctuating electricity generation are expected to be the most exergy efficient renewable gases due to the short conversion chain compared to e.g. e-fuels. The two analysed scenarios indicated a total electricity demand of about 117 TWh/a in 2050. In the same year, the total renewable gas demand ranges between 99 and 125 TWh/a. For both scenarios and all considered years, the electrical self-sufficiency was at least 92%. In contrast, the technical national renewable gas production (including wood gasification, biogas plants and electrolysis) could only cover between 43 and 59% of the total renewable gas demand in 2050, although the extensive renewable generation expansion. According to the two scenarios, in 2050, an import of renewable gases between 40 and 72 TWh/a is required. A decarbonised business-as-usual scenario results in a renewable gas import demand between 210 and 250 TWh/a in 2050. For comparison, Austria had a net import of 285 TWh/a fossil energy carriers in 2018 [16].

Accordingly, the rapid expansion of renewable energy sources, as well as implementation of energy efficiency and sufficiency measures, are not mandatory to achieve complete decarbonisation of Austria. Instead, decarbonisation can also be realised exclusively by renewable imports (if available). However, huge import demand leads to major dependencies on exporting countries. Moreover, it is also associated with the outflow of nationally created wealth abroad. The alternative is to reduce import dependency by reducing primary energy consumption (via efficiency and sufficiency measures), expanding renewable generation, and building grids, storages and electrolysis plants. This can increase Austria's economic performance and will strengthen Austria as a technology centre. At the same time, the costs for imported and nationally produced green hydrogen are comparable.

Besides Austria, many other European countries will probably also require renewable imports in future. However, it is currently unclear which country/region will export renewable gases on a large scale. Furthermore, exporting countries or regions must ensure many aspects such as the ecological impact, the social responsibility or the actual CO_2 footprint to enable sustainable decarbonisation.

Finally, the following non-regret measures can be derived from this entire thesis:

- Significant reduction of primary energy consumption through efficiency and sufficiency measures
- Rapid expansion of renewable energy sources, nationally and internationally
- Planning and construction of electrolysis plants and storages, nationally and internationally
- Development of economically, ecologically, and social robust international renewable gas import concepts and rapid construction of the necessary infrastructure

6 OUTLOOK

More future research can be carried out based on the methodology, the models and the findings. In addition, results such as the technical renewable exergy potentials as well as the useful energy demands can be reused in other studies. In the following, only the improvement and additional applications of the optimisation model is discussed in detail.

The optimisation model could be further developed to answer more research questions. Relevant would be the integration of spatial and infrastructural aspects. Austria should be organised in cells to address these aspects. To achieve a more precise exergy assessment compared to the current model, it would be possible to include exergy expenditure for the construction of all conversion units, storages and grids. This could be achieved by including concepts such as the cumulative exergy consumption (CExC) [40]. CExC ensures that the exergy expenditure for construction justifies the exergy advantage in operation. In addition, CExC could improve the consideration of international exergy losses for imported energy as the entire energy conversion chain is considered.

In addition to the extension of the model, the model can also be analysed more in detail. This includes the robustness of the results for different scenarios (changing boundary conditions such as import/export limitations, renewable generation, demand or efficiencies). Thereby a deeper understanding of the entire national energy system can be gained. Furthermore, the contribution of one single conversion unit efficiency to the overall efficiency can be investigated. This investigation can be used to determine which technology is most important for further development.

This model can be used to analyse various possible transformation strategies to find the optimal one for Austria. These strategies can include various limitations such as the available technologies, maximum power of conversion units, maximum/minimum penetration rates or maximum grid capacities. In addition, barriers and drivers can be identified. On top, a comprehensive cost analysis in post-processing including all conversion technologies, renewable energy sources, girds and storages can help ensure economic feasibility. This cost analysis can also be used to determine necessary subsidies. All these further developments can be used to find a comprehensive and feasible transformation strategy for Austria to achieve full decarbonisation.

Finally, the model can be applied to other countries or regions to generate valuable information for a national decarbonisation there. Furthermore, results of other countries/regions could be compared with those of Austria to identify correlations, gain even deeper knowledge and develop international decarbonisation strategies.

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Appendix A: Peer-Reviewed Publications

First Journal Article

Sejkora, Christoph; Kühberger, Lisa; Radner, Fabian; Trattner, Alexander; Kienberger, Thomas (2020): Exergy as Criteria for Efficient Energy Systems-A Spatially Resolved Comparison of the Current Exergy Consumption, the Current Useful Exergy Demand and Renewable Exergy Potential. In: *Energies* 13 (4), S. 843. DOI: 10.3390/en13040843.

Published online: February 14th, 2020

Table A 1. Author statement to the first journal article

Activity	**Contributing authors (the first-mentioned is the main author)**
Conceptualisation	C. Sejkora, T. Kienberger
Methodology	C. Sejkora, T. Kienberger
Data curation	C. Sejkora, F. Radner
Software development and validation	C. Sejkora, A. Valanne, T. Grandl
Modelling	C. Sejkora
Investigation and analysis	C. Sejkora, L. Kühberger, F. Radner
Visualization	L. Kühberger, C. Sejkora, F. Radner
Writing (original draft)	C. Sejkora, L. Kühberger, F. Radner
Writing (review and editing)	C. Sejkora, T. Kienberger, A. Trattner

energies

MDPI

Article

Exergy as Criteria for Efficient Energy Systems—A Spatially Resolved Comparison of the Current Exergy Consumption, the Current Useful Exergy Demand and Renewable Exergy Potential

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Abstract: The energy transition from fossil-based energy sources to renewable energy sources of an industrialized country is a big challenge and needs major systemic changes to the energy supply. Such changes require a holistic view of the energy system, which includes both renewable potentials and consumption. Thereby exergy, which describes the quality of energy, must also be considered. In this work, the determination and analysis of such a holistic view of a country are presented, using Austria as an example. The methodology enables the calculation of the spatially resolved current exergy consumption, the spatially resolved current useful exergy demand and the spatially resolved technical potential of renewable energy sources (RES). Top-down and bottom-up approaches are combined in order to increase accuracy. We found that, currently, Austria cannot self-supply with exergy using only RES. Therefore, Austria should increase the efficiency of its energy system, since the overall exergy efficiency is only at 34%. The spatially resolved analysis shows that in Austria the exergy potential of RES is rather evenly distributed. In contrast, the exergy consumption is concentrated in urban and industrial areas. Therefore, the future energy infrastructure must compensate for these spatial discrepancies.

Keywords: exergy; efficient energy systems; spatially resolved comparison; renewable energy sources; potential; total energy consumption; primary energy consumption; energy system planning; Austria-wide comparison

1. Introduction

Major systemic changes in the energy system, such as the transformation from fossil-based energy sources to renewable energy sources (RES), are necessary in order to achieve climate neutrality in Europe. This is an enormous challenge, since the renewable share of the gross available energy is only 14% (as the average in a range of min. 5 % in Netherlands and Malta, and max. 43 % in Latvia) in Europe (EU-28) in 2017 [1]. In this context, in the same year, Austria had a gross inland consumption, equal to the gross available energy, of 401 TWh/a, of which 29% came from renewable sources [1,2]. When developing suitable energy transition strategies for Austria, in order to increase the share of renewables from 29% to 100%, the following central questions must be addressed:

- Which technologies for final energy applications should be used in which case? How will these technologies affect energy consumption in the future?

- Where should renewable energy sources be utilized in the future and to what extent?
- What must the energy infrastructure (e.g., grids, storages, etc.) of the future look like in order to be able to compensate for all temporal and spatial fluctuations of the renewable generation?
- To what extent can energy consumers help the energy infrastructure to compensate for the spatial and temporal fluctuations?
- Is it reasonable to achieve energy self-sufficiency? If not, how much energy of which energy carrier must be imported?

The answer to these questions requires a comprehensive data set, which includes, amongst others, the following information:

- spatially and temporally resolved actual demand of energy services of all sectors by purpose
- spatially and temporally resolved current consumption of final energy applications per technology
- spatially and temporally resolved current energy consumption of all sectors, including all conversion and transport losses, per energy carrier
- spatially and temporally resolved potentials of RES
- spatially resolved current energy infrastructure including its temporally and spatially resolved workload

In order to obtain the maximum possible amount of information, the data set used should be exergy based. In contrast to energetic analyses, exergy analyses offer a deeper insight into and understanding of the energy system, since it also considers the quality of energy. Exergy describes how much of the energy can be transformed to any other form of energy. Additionally, exergy allows a comparison of different forms of energy (Section 2.1).

Exergy analyses of countries help to locate the sectors with the greatest potential for savings (Section 3.1). Such analyses have already been made for various countries, including Austria [3]. However, this study about Austria is not spatially resolved.

For Austria, there are only two spatially resolved energy consumption studies available at this point (Section 3.2): one focused on only the industrial sector (including transport and conversion losses) [4] and the other one took the final energy consumption of all sectors into account, but neglected the transport and conversion losses [5]. None of these two Austria-relevant studies were exergy based.

Furthermore, there are only two studies [4,6] published which have dealt with the spatially resolved potential of RES in Austria (Section 3.3). However, neither of them took exergy into account. Exergy enables the comparability of different renewable energy forms (e.g., heat or electricity) and technologies (e.g., photovoltaics vs. solar thermal systems). Most of the current energy infrastructure, such as the electrical grids, pumped-storage plants or thermal power plants, is well documented and the information is made publicly available by the operators.

As there is no comprehensive data set for Austria available, this study analyses the country's current situation. Therefore, this study will answer important questions about the national energy transition. For this purpose, a spatially resolved exergy analysis of the total Austrian energy consumption, as well as an exergy based and spatially resolved analysis of the potential of RES, is made. This analysis explicitly does not take temporal considerations into account. The schematic overview of the paper is shown in Figure 1.

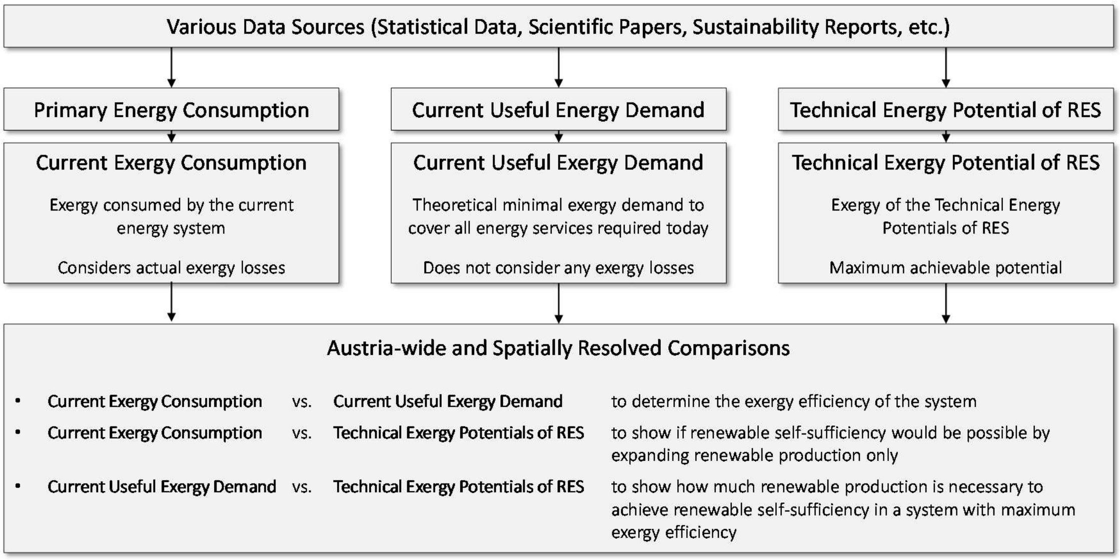

Figure 1. Schematic overview of the paper. First, the three exergy amounts—current exergy consumption, current useful exergy demand and technical exergy potential of renewable energy sources (RES)—are determined. Then, they are compared in a spatially resolved way, as well as on a country-wide level, to comprehensively analyze the situation in Austria.

First, based on a variety of data sources, the three so-called exergy amounts—current exergy consumption, current useful exergy demand and technical exergy potential of RES—are determined. Then, these three exergy amounts are compared on an Austria-wide and spatially resolved level, in order to answer the following research questions:

- What is the exergy efficiency of the current Austrian energy system?
- Is it possible to cover the current exergy consumption by the exergy potentials of RES in Austria?
- How much renewable production is necessary to achieve renewable self-sufficiency in a system with maximum exergy efficiency?
- What do these comparisons look like on a spatially resolved level?

In Section 2, the exergetic fundamentals (Section 2.1) and essential definitions from the field of energy statistics (Sections 2.2 and 2.3) are explained. In Section 3, the state of research in the area of exergetic analysis (Section 3.1), in the area of spatially resolved energy modeling (Section 3.2) as well as in the area of potential of RES (Section 3.3) is presented, since it is the basis for the methodology (Section 4).

2. Fundamentals and Definitions

This section first explains the basic principles of exergy (Section 2.1) and afterward, statistical definitions are presented (Sections 2.2 and 2.3).

2.1. Exergy

Energy can be divided into its parts, exergy and anergy, according to Equation (1)

$$energy = exergy + anergy \tag{1}$$

Any lack of mutual stable equilibrium between a system and the environment can be used to produce technical work [7]. A system can provide its maximum technical work during the reversible transition from the initial condition to the surrounding conditions. This "workability" is referred to as exergy. Derived from the first (FLT) and the second law of thermodynamics (SLT) the following statements are applicable [8]:

- Energy as the sum of anergy and exergy stays constant during all processes. (FLT)
- All irreversible processes transform exergy into anergy. (SLT)
- During a reversible process the exergy stays constant. (SLT)
- It is not possible to transform anergy into exergy. (SLT)

All natural and technical processes are lossy and transform exergy into anergy. The loss of exergy in a process ex_{L} can be used to describe the irreversibility of a process and is directly linked to the increase in irreversible entropy gain dS_{irr}. Different forms of energy consist of different fractions of anergy and exergy. Furthermore, the exergy can be split into chemical, electrical and thermomechanical exergy, according to Figure 2. The nuclear exergy fraction is neglected in this paper. Anergy is already in full thermodynamic equilibrium with the environment. The thermomechanical exergy contains physical, kinetic and potential energy which deviates from the environment. If the mechanical and thermal equilibrium of a system is reached, this system cannot perform technical work anymore. The chemical exergy contains the chemical bond energy and the mixing energy of its reaction products. If material equilibrium is reached and the Gibbs free energy reaches its minimum, the chemical exergy is equal to zero. If both thermomechanical and chemical equilibrium are reached, the system is in full thermodynamic equilibrium with the surroundings and all exergy with respect to the surrounding conditions is processed. The system can no longer provide any work, the substance is in thermodynamic equilibrium with the environment and its energy fully consists of anergy. The exergetic part of the energy is the driving force for all technical and natural processes. Thus, it has economic value and is worth managing carefully [7]. In conclusion, although energy is a conserved quantity and cannot be destroyed, it has to be used considerately in order to avoid irreversible exergy losses.

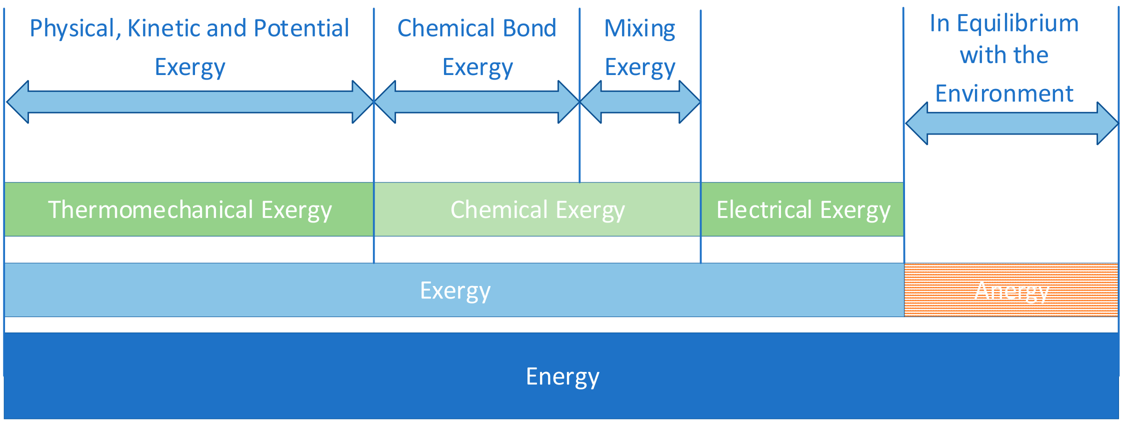

Figure 2. Energy divided into its fractions anergy and exergy. Anergy is in full thermodynamic equilibrium with the environment, while exergy forms thermomechanical exergy, chemical exergy, and electrical exergy. Nuclear exergy is neglected. Following [9].

Exergy can be used to assess the quality of an energy form. This is illustrated with the exergy factor, defined as the maximum achievable exergy to energy ratio. An exergy factor of 1 describes a fully usable energy form, an exergy factor of zero describes an unusable energy form without any exergy share. The exergy factors for different energy forms are listed in Table 1. The important energies of technical processes (thermal, electrical, mechanical and chemical energy) are discussed in detail in the following sections.

Table 1. Exergy factors for various energy forms; following [7].

Energy Form	Exergy Factor in 1
Mechanical Energy	1
Electrical Energy	1
Chemical Fuel Energy	~1 [1]
Nuclear Energy	0.95
Sunlight	0.9
Hot Steam at 600 °C	0.66 [2]
District Heating at 90 °C	0.18 [2]
Space Heating at 30 °C	0.02 [2]

[1] Depending on the definition of the environment and the chemical substance. [2] Strongly depending on the surrounding temperature, calculated with 25 °C surrounding temperature.

2.1.1. Electrical and Mechanical Energy

Electrical energy and mechanical energy are entirely technical work w_t. Technical work as shaft work is, in theory, fully convertible into different energy forms and can therefore be considered pure exergy ex_W, as displayed in Equation (2).

$$ex_W = -w_t \tag{2}$$

2.1.2. Thermal Energy

According to the second law of thermodynamics, it is not possible to transform thermal energy q fully into technical work, because thermal energy consists in part of anergy. However, the part of thermal energy that differs from the surrounding state can be used. If the thermal energy is supplied at the highest possible temperature T and emitted at the surrounding temperature T_S, the maximum technical work is gained. In practice, the upper temperature T is limited by the materials used [10]. The exergy of the thermal energy ex_Q can thus be described with Equation (3). Thermal energy and exergy are linked by the Carnot Factor η_C.

$$ex_Q = q \cdot \left(1 - \frac{T_S}{T}\right) = q \cdot \eta_C \tag{3}$$

When the temperature T is lower than the temperature of the surrounding T_S the Carnot Factor is negative. The relation of exergy ex_Q to thermal energy q over the temperature shows that the exergy demand is significantly higher for cooling processes than for heating processes. To keep the temperature of a system below the surrounding temperature T_S, exergy has to be transferred in the opposite direction to the thermal energy.

2.1.3. Chemical Energy

When a chemical substance reacts reversibly with the surrounding substances, chemical exergy is gained equivalent to its Gibbs free energy $\Delta_R G^0$. The reaction products are present at T_S and the pressure of the surrounding environment p_S. By the reversible mixing of the reaction products with the environment, mixing exergy is obtained. The amount depends on the chemical composition of the surrounding conditions. The chemical exergy gained from chemical reactions and mixing with the environment can be calculated with Equation (4), whereby $\nu_{st\ i}$ is the stoichiometric coefficient of component i, R_m is the molar gas constant and n_i is the number of moles of component i [11]. The standard pressure is represented by $p_0 = 1.01325$ bar.

$$ex_{CH} = -\Delta_R G^0 + n_i \cdot R_m \cdot T_S \sum_i \nu_{st\ i} \cdot \ln \frac{p_0}{p_{S\ i}} \tag{4}$$

To determine the chemical energy of a substance, reference environmental conditions containing all chemical reaction products have to be chosen. The exergy of fuels ex_{f} is defined by Equation (5).

$$ex_f = \gamma_{\mathrm{f}} \cdot H_{\mathrm{f}} \tag{5}$$

The exergy grade γ_{f}. of a fuel is defined as the ratio of the higher heating value H_{f} to the chemical exergy ex_f at specific surrounding conditions. The exergy grade for selected fuels is listed in Table 2.

Table 2. Exergy grades for selected fuels at 25 °C and $p_0 = 1.01325$ bar [7,8,12].

Fuel	**Higher Heating Value** H_{f} **in kJ/kg**	**Chemical Exergy in kJ/kg**	**Exergy Grade** γ_{f} **in 1**
Gasoline	47,849	47,394	0.99
Natural Gas	55,448	51,702	0.93
Hydrogen Gas	141,789	116,649	0.83
Carbon	32,765	34,174	1.04
Crude Oil	42,414	44,800	0.94

2.1.4. Energy and Exergy Efficiency

Technical processes and energy systems can be assessed based on their energy and exergy efficiencies. The energy efficiency η is defined as the ratio of energetic benefit en_{ben} to energetic effort en_{eff}, as in Equation (6) and Figure 3. Similar to this definition, the exergy efficiency ζ is defined as the ratio of exergetic benefit ex_{ben} to exergetic effort ex_{eff}, as shown in Equation (7).

$$\eta = \frac{en_{\mathrm{ben}}}{en_{\mathrm{eff}}} = 1 - \left[\frac{en_{\mathrm{loss}}}{en_{\mathrm{eff}}}\right] \tag{6}$$

$$\zeta = \frac{ex_{\mathrm{ben}}}{ex_{\mathrm{eff}}} = 1 - \left[\frac{ex_{\mathrm{waste}} + ex_{\mathrm{dest}}}{ex_{\mathrm{eff}}}\right] = 1 - \left[\frac{ex_{\mathrm{loss}}}{ex_{\mathrm{eff}}}\right] \tag{7}$$

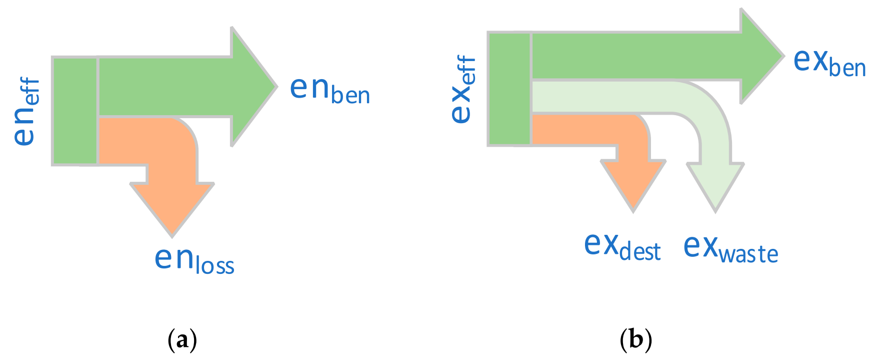

Figure 3. (**a**) Definition of energy effort (system input), usable energy benefit and unused losses (system output); (**b**) Definition of exergy effort (system input), irreversible exergy destruction, unused exergy waste and used exergy benefit (system output).

Both equations can be illustrated as the ratio of loss to input. For exergy, a distinction has to be made between exergy waste ex_{waste} and exergy destruction ex_{dest}:

- Exergy destruction describes the irreversible transformation from exergy into anergy during a process such as providing low temperature heat from a highly exergetic energy carrier such as natural gas.
- Exergy waste is the unused share of exergy in a discharged waste energy flow, such as exhaust gas of an internal combustion engine.

Exergy destruction and exergy waste are summarized in the exergetic losses ex_{loss}. The exergetic benefit is defined as the exergetic effort less the exergetic losses ex_{loss}.

Energetic efficiency is a process-dependent ratio of energy benefit to energy effort. Energy sources of different qualities are, following the first law of thermodynamics, mixed without distinction. In contrast to exergetic efficiency, it does not quantify energy degradation (Figure 3). Energy efficiencies also do not allow conclusions to be drawn regarding possible improvements for the process considered. For example, an adiabatic gas boiler transforms chemical energy into thermal energy with an energy efficiency close to $\eta = 1$. Due to the inevitable exergy destruction during the transformation from chemical to thermal energy, the exergy efficiency is $\zeta \ll 1$. This indicates that high-quality energy is transformed into a low-quality energy form during the process. When exergy is transformed into anergy, usable energy is lost. If additional heat losses to the surrounding environment, for example through hot exhaust gases, are considered, this part of the thermal exergy would be lost to the environment and become exergy waste. Briefly summarized, the exergy efficiency ζ clearly displays how closely a process operates to the theoretical, reversible optimum. In general, this is not true for the energetic efficiency [7].

Exergy and anergy flows can be calculated on the basis of energy flows, reference conditions of the environment, and technical processes of the considered energy system. Subsequently, exergy waste and exergy destruction can be calculated for every conversion step of all energy system elements. This quantitative evaluation approach can help to identify potential improvements when it comes to reducing the primary energy and fossil fuel demand. Additionally, the best energy carrier can be selected if the quality of the needed energy form is taken into account. Thus, the exergy efficiency of energy supply paths can be improved. Exergy waste is an indicator of potential environmental influences. Every exergy waste flow is able to alter the environment [9], but it can also be used to cover the exergy demand of other processes. Such cascaded energy systems can help to reduce the total exergy demand and increase the exergetic efficiency. Additionally, exergy analysis allows for the qualitative comparability of different technologies.

2.2. Definitions of Primary, Secondary and Final Energy

Primary energy carriers are energy carriers that can be found as natural resources, such as coal, crude oil or natural gas. They can be converted into secondary energy carriers through conversion processes, e.g., to simplify transport or utilization. Secondary energy carriers can only be provided by conversion. Examples for secondary energy carriers might be electricity, hydrogen, district heating, gasoline or diesel. Since conversion processes always cause losses, the secondary energy output is always lower than the primary energy input [13].

Final energy is the energy that is actually used by the final consumer, which means that in contrast to primary and secondary energy, transport and distribution losses are also taken into account. Therefore, it is equal to primary energy minus conversion losses and minus transport and distribution losses [14].

In accordance with International Energy Agency (IEA) guidelines, renewable energy carriers are in some cases classified as primary energy carriers (e.g., woody biomass) and in other cases as secondary energy carriers (e.g., electricity from photovoltaic systems or wind power plants). The first practically multiple usable energy carrier is always chosen. [15]

2.3. Definitions of Energy Consumption and Energy Supply

Some specific terms and definitions are necessary for describing the energy system on a national level, as it is considered in this work. In this section, the most important terms will be defined (according to the definition used by Statistics Austria [16]):

The Gross Inland Consumption (GIC) is the sum of the Indigenous Production of Primary Fuels (IP), the difference between Import (Imp) and Export (Exp), as well as the Stock Change (ΔStock). The

GIC, which is also called the Total Energy Supply, describes the total nationwide energy consumption (Equation (8)).

$$GIC = IP + Imp - Exp \pm \Delta Stock \tag{8}$$

In contrast to Equation (8), which defines the GIC based on the energy supply, the GIC can also be calculated based on the energy consumption. This is the sum of the Consumption of Energy Sector Use (CES), the Transport Losses (TL), the Non Energy Use (NEU), the Final Energy Consumption (FEC) and the Transformation Input (TI) minus the Transformation Output (TO) (Equation (9)).

$$GIC = CES + TL + NEU + FEC + TI - TO \tag{9}$$

For clarification, the difference between the transformation output and input is the sum of all energy conversion losses. Fuels used as materials input, e.g., in the chemical industry, are labeled as non energy use. In addition, the CES defines the energy demand, required for the supply of secondary energy (e.g., the electrical energy demand of power plants).

The imports and exports consider primary as well as secondary energy. Therefore, by combining Equations (8) and (9), it can be determined that the GIC only takes conversion losses into account, which are within the system boundaries. This corresponds to the IEA specification [14] and must be taken into account when creating energy balance statistics in order to avoid double accounting. For example, country A imports electricity from country B, which uses a coal-fired power plant to generate electricity. In this example, the energy losses of the electricity generation are only included in the energy balance statistic of country B, even though the electricity is consumed by country A.

In comparison to the GIC, the primary energy consumption (PEC) does not include the NEU (Equation (10)) [17]. Therefore, the PEC describes the total energy used for energy purposes. According to the IEA guidelines [13,14], it includes primary energy production as well as net imported primary and secondary energy.

$$PEC = GIC - NEU \tag{10}$$

3. State of Research

In this section, a brief overview of published studies relevant for this paper is presented. For each of the three exergy amounts of Figure 1, a spatial separation as well as an exergetic assessment of the energy must be performed (Figure 4). Therefore, the exergetic assessment of energy systems is discussed in Section 3.1. Furthermore, in Section 3.2, a short overview of the possibilities of spatial separation of energy consumptions or potentials is given.

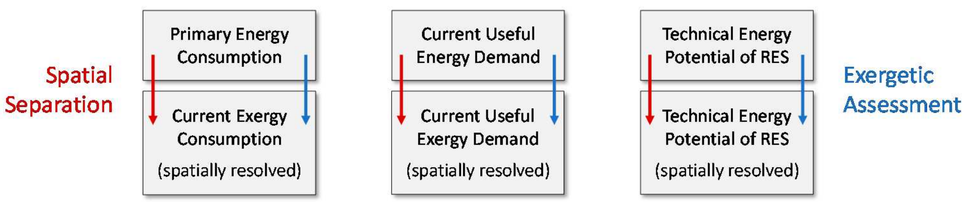

Figure 4. The spatial separation, as well as the exergetic assessment, is required for each of the three exergy amounts.

For methodological reference, Section 3.3 presents the different types of renewable potential studies. Furthermore, a selection of international and national studies is shown, and the different assumptions are discussed. The Austrian studies can also be used as a reference for the potentials calculated in this paper.

3.1. Exergetic Assessment

This section focuses on the exergetic assessment of energy systems. Therefore, a general overview is given in Section 3.1.1. As this paper addresses a large-scale system, selected case studies of such energy systems are discussed in Section 3.1.2. When determining the overall efficiency of large-scale systems, on the one hand the efficiency of the energy supply and on the other hand the efficiency of the final application have to be taken into account. Since the efficiency of the energy supply can easily be calculated based on published statistical data, the relevant exergy efficiencies of final energy applications are presented in Section 3.1.3.

3.1.1. Exergy Analysis: An Overview

Exergy analyses have been a field of special interest for more than 30 years now. Since exergy itself not only is a measure of quantity but also of quality [7,18], additional information can be obtained with exergy analysis. Dincer and Rosen [7] state that because these methods of analysis aim to detect energy inefficiencies, they allow for a much better identification of the causes and locations of energy losses (Section 2.1). Due to these and other advantages compared to the sole execution of energy analyses, exergy analysis is used in many different research areas:

Extensive information on different fields of application can be found, for example, in Dincer and Rosen [7]. According to [7], exergy analysis can be used, for instance, in fields like policy development, large-scale systems like countries, or application processes (e.g., heat pumps, cogeneration or renewable energy systems). The authors also presented the field of exergoeconomics, a combination of economic and exergy analysis, which can be used for both micro- and macroeconomic analyses [7].

For combining economic and exergy analysis, various approaches are available. These also include non-exergetic expenditure (e.g., labor, finance, environment), such as the concept of Extended Exergy Accounting (EEA) introduced by Sciubba [19]. This reference stated that exergy has an intrinsic, strong and direct correlation to economic values [19]. Another approach which combines exergy and economy, is the concept of exergetic costs by Lozano and Valero [20]. The cumulative exergy consumption (CExC) method, introduced by Szargut and Morris [21], describes how much exergy in total was needed to provide a product or a service [22]. Lazzaretto and Tsatsaronis [23] presented the specific exergy costing (SPECO) method that clearly defines the fuel and product of system components. They compared their approach to other concepts. A more detailed bibliography for different methods in this field can be found in Sciubba and Ulgiati [24], Sciubba et al. [25] or Sciubba and Wall [26].

Besides technical and economic analysis and aspects, Dewulf et al. [27] noted that exergy analyses are used for many other areas. They stated that especially environmental impact analysis is one of the most mature fields of application when talking about Environmental Science and Technology. Additionally, Szargut [28] described applications in the field of ecology (e.g., exergy losses of living organisms) as promising, which was proven by the work of authors like Jørgensen, Nielsen and Bastianoni (e.g., [18,29,30]), whereas an application to social sciences can be considered unsuitable for the concept.

After this general overview of the wide range of applications of exergy analysis, large-scale systems such as countries will be discussed in detail in the following section, since this paper focuses on such a system.

3.1.2. Exergy Analysis of Large-Scale Energy Systems

To perform exergy analysis on large-scale systems, it is useful to consider them as thermodynamic systems because that allows the application of mass- and energy conservation [25]. Based on this assumption, exergy analysis has been performed for different large-scale systems. Exergy analysis of systems like countries, regions or sectors allows the identification of areas for large improvements regarding exergy efficiency [7]. [7] noted that these analyses provide insights into the efficiency of a society's use of resources as well as information to balance economic aspects and efficiency issues.

When comparing studies, differences with regard to the system boundaries but also to the considered variables can be identified. Another difference lies in the intended outputs. Some examples of different system boundaries and methods are mentioned in the following:

- Ertesvåg [31] identified two main basic calculation approaches for exergy analysis of countries: Reistad's approach [32] and Wall's approach [33]. To receive exergy efficiencies, Reistad only took the flows of energy carriers for energy use into account, whereas Wall also considered material flows (e.g., wood, ores).
- Some studies considered useful exergy as beneficial (e.g., [7,34,35]), whereas others aimed to present the amount of the production output instead (e.g., [18]).
- EEA depicts the society in its entirety and does include non-material or energy-based aspects, such as capital, labor and environment [25].
- CExC is a resource-to-end-use calculation method and analyses the whole production line starting with raw materials and ending with the finished product or service. CExC results therefore present the total exergy consumption caused by the production process [21,22].

Although they all follow the basic principle of exergy theory, it is hard to compare results due to further specifications regarding the exact research interest. A short overview of research in the field of exergy analysis of large-scale systems is given in the current section.

Reistad's famous exergy analysis of the United States of America in the 1970s seems to be the first analysis of a country considered as a large-scale system. Since then, many other countries and regions, as well as sectors, have been analyzed. A comprehensive comparison of exergy efficiency studies for more than 10 countries was performed by Ertesvåg [31]. He concluded that the exergy efficiencies of final applications range between 20% and 30% and the total exergy efficiencies for the countries analyzed (e.g., Norway, Canada, USA) range between 9% and 28%.

Utlu and Hepbasli [36] also compared different studies (some of which were also part of the analysis done by [31]) for various years and determined the total exergy efficiency of the considered countries to be between 15% and 39%. In contrast to the exergy efficiency of final applications, the total exergy efficiency takes the whole energy system into account, including both losses of the energy supply and losses of the final application.

Utlu and Hepbasli [37] used an approach proposed by Rosen and Dincer [38], which is very similar to Reistad's approach, in order to calculate exergy efficiencies for four sectors (utility, industry, transport, commercial and residential sector) of Turkey for 1999 and 2000. The efficiencies range between 8% (commercial and residential sector in 2000) and 36% (transport in 1999).

Nielsen and Jørgensen [39] conducted a sustainability analysis based on exergy analysis for different sectors of the Danish island Samsø. They implemented a hierarchical and geographical based system and methodology. Skytt et al. [40] adapted the method of [39] and applied it to the larger scale system of Jämtland in Sweden and additionally included further considerations about the application of material flows.

A study performed by Koroneus et al. [41] about energy and exergy utilization in Greece for the residential and industrial sectors in 2003 showed exergy efficiencies of 21% (residential sector) and 51% (industrial sector).

Rosen [42] dealt in particular with efficiencies in the industrial sector. To perform the evaluation, he analyzed each industry sector (e.g., iron and steel, construction) separately. Then, he combined them to get the overall industrial exergy efficiency. The global industrial exergy efficiency is proposed as 30%.

Lindner et al. [9] conducted an exergy analysis for Germany and came to the conclusion that energy carriers with a high exergy content, such as oil or gas, are used for fundamentally wrong purposes. This caused a total exergy efficiency of only 18% in Germany.

A similarly low total exergy efficiency of 21% can be found in Gutschi et al. [3]. This study dealt with exergy flows in Austria in 1956 and 2005. The highest exergy destruction occurs in space heating applications, where energy carriers with high exergy content (e.g., gas) are used to provide heat on a low temperature level. The usage of heat pumps or of combined heat and power plants would be better.

Other studies also included financial aspects in their considerations. These extended exergy accounting analyses can also be used on national or regional scales, as seen in Sciubba et al. [25] for the case of Siena or Ertesvåg [43] for Norwegian society.

All these exergy efficiency key figures support one central point—that the current energy systems lack efficiency in the use of exergy and therefore offer enormous potential for optimization and savings.

3.1.3. Exergy Efficiency of Final Energy Applications

In order to calculate the useful exergy demand from the useful energy demand, the exergy efficiencies of final energy applications are necessary. For the Austrian road traffic sector, the exergy efficiencies of the vehicle pool based on distance driven per vehicle category have been calculated. The average exergy efficiency of the Austrian internal combustion engine (ICE) vehicle pool in 2018 was 27% when transforming final energy to the useful energy form of traction. Only the traction energy is defined as a benefit. In that case, energy and exergy efficiencies are equal. If all vehicles fulfilled the newest emission standards, the efficiency would increase only slightly to 29%. The exergetic efficiency of vehicles could be substantially improved if electric mobility such as battery electric vehicles and fuel cell vehicles are used. These values are provided by the Institute of Internal Combustion Engines and Thermodynamics (Graz University of Technology) and HyCentA (publication in process).

The efficiencies of other final energy applications and gas transport are listed in Table 3. The efficiency of diesel trains in Austria can be indicated by 28% to 30%. In general, light-emitting diode (LED) lamps can reduce the final energy and exergy consumption by substituting light bulbs. Based on the efficiency of stationary diesel engines and a propulsion efficiency of 40%–65% [44], the efficiency of ships is stated as 15%–30%. The theoretical efficiency of electrical stationary engines of over 90% is not attained. According to [45], the mean electric motor efficiency is currently 79%. Due to losses in components such as gears, breaks, valves and control units the efficiency of electric motor applications can be as low as 20%–40% [46]. On average, the efficiency of stationary electric motor applications is 50% and can be further improved by 20%–30% [45].

Table 3. Exergy and energy efficiencies of other final energy applications.

Technology	Exergy and Energy Efficiency $\zeta = \eta$ in %
Railway [1]—Diesel	28 [2]–30 [3]
Railway [1]—Electric	65 [2]–85 [3]
Aircraft [7]	20–28
Ship—Diesel	15–30
Stationary Electric Motor Systems [45]	50
Stationary Diesel/Gas Engines [47]	42–50
Lighting—Halogen [48]	12–15
Lighting—Fluorescent Lamp T5 [48]	24
Lighting—LED [48]	42–49

[1] Efficiencies have been calculated with a longitudinal dynamics model by HyCentA, [2] With interior heating, [3] Without interior heating.

While discussing the efficiency of final energy applications, long-distance gas pipelines must also be considered, according to the definition of Statistics Austria [49]. The long-distance pipelines are primarily used for supra-regional and international gas trading and not for domestic supply. When the gas in the pipeline is used to fuel the gas compressor station, the compressor efficiency of 75%–84% and the efficiency of the gas turbine used to operate the compressor of 28–35% have to be taken into account [50]. Gas compressor stations typically use less than 1% of the transported gas to power the compressors [51].

3.2. Spatially Resolved Energy Modelling (Top-Down and Bottom-Up)

Two basic modeling approaches are generally used in the field of spatial energy modeling: top-down and bottom-up. Depending on the available data and purpose, it is necessary to choose one, although, a hybrid approach with a combination of both might also be reasonable. Bottom-up analysis uses disaggregated data that are later aggregated and extrapolated to obtain results. The top-down analysis relies on aggregated data which are then split up for the task at hand [52,53]. These modeling techniques are therefore methodologies in a reverse direction [54]. Other widely used modeling techniques are based on Index Decomposition Analysis (IDA) methods. By first defining a governing function, it is possible to connect the aggregate to be decomposed to pre-defined factors of interest and then quantify the component's effect on the system [55]. According to Fengling's [54] study about decomposition analysis' application to energy, these methods can also be considered as top-down approaches.

Bottom-up approaches, like statistical analysis (e.g., linear regression), can be used for predicting residential energy consumption as was shown by Fumo and Rafe Biswas [56]. They stated that, according to a literature review, regression analysis is feasible for model development in this sector. Kazemi et al. [57] also used a regression model for the forecasting of the industrial energy demand of Iran. Scarlat et al. [58] performed a spatial analysis of biogas potential from manure in Europe following a bottom-up approach by aggregating the manure produced by all livestock units in a spatial unit.

Angelis-Dimakis et al. [59] analyzed different top-down methods to evaluate the availability of renewable energy sources, such as wind and solar resource potentials. The authors remarked that, especially for RES, a strong geospatial connection prevails. In the study of Fleiter et al. [60], researching barriers of energy demand models, the authors claimed that top-down models often represent economist's viewpoints whereas bottom-up models follow technological pathways. Top-down models are therefore suitable for the modeling of interactions between energy systems and economic variables. As discussed in Koopmans and te Velde [61], top-down models propose lower energy efficiency and higher energy demand than bottom-up models. Due to that, hybrid approaches are a reasonable alternative.

Li et al. [62] discussed model techniques of urban building energy use. As seen in other publications, they distinguished top-down and bottom-up approaches that are both used in combination with Geographical Information Systems (GIS). Abart-Heriszt et al. [5] linked bottom-up and top-down methods to perform a spatially differentiated analysis of final energy consumption patterns and associated greenhouse gas emissions on a municipal level in Austria. Ramachandra and Shruti [63] also applied top-down and bottom-up techniques for the spatial mapping of renewable energy potentials in Karnataka, India.

The results of the modeling approaches presented in this section can be used for geospatial applications and visualization afterward. Therefore, the spatial units have to be chosen individually for each case, depending on the modeling approach and data availability. Depending on the available data, it is possible to transform these models to different scales such as regional or national.

3.3. Potential of Renewable Energy Sources (RES)

In principle, a distinction can be made between the theoretical potential, the technical potential, and the reduced technical potential.

The theoretical potential is described by the physical supply within a certain scope. It represents the upper physical boundary and does not consider ecological, economic, social, structural or administrative aspects. For example, the theoretical biogas potential for Germany is defined as the proposed maximum methane yield per hectare multiplied by the area of Germany [64].

The technical potential is based on the theoretical potential but considers state of the art technologies and is reduced by the actual structures of the society (e.g., building and road infrastructures, the amount and composition of waste or the amount of livestock). There is no consideration of changes in the current structures (e.g., changes in land use), of economic aspects, of different paths of utilization, of feasibility or of social aspects.

The reduced technical potential or the economic–technical potential can be calculated by taking additional criteria such as political conditions, different utilization pathways or economic aspects into account.

3.3.1. International RES Potential Studies

Potentials of RES are published in numerous international studies and vary greatly in their values. Most of these studies present data on technical potentials for different energy carriers such as solar energy, wind energy, hydro energy, biomass, geothermal energy and ocean energy.

IPCC [65] presents the technical potentials of six different renewable energy carriers. In contrast to other studies, biomass and solar energy are presented as primary energy because of its diverse forms of use. The total worldwide potential ranges between 1895 and 52,802 EJ/a (about 526 to 14,667 PWh/a). Rogner et al. [66] show a total technical potential between 67,510 and 294,625 EJ/a (about 18,753 to 81,840 PWh/a) for the same energy carriers as [65].

Many studies also offer country- or state-level data. However, due to scale and a multitude of assumptions, there are enormous differences between various studies, and it is hard to compare the results in detail.

Exergetic analysis itself is only performed for different RES applications such as solar energy like seen in Saidur et al. [67], Park et al. [68] or Svirezhev [69]. No studies on spatially resolved exergy potentials that operate nationwide on district level could be found.

3.3.2. RES Potential Studies in Austria

There are a few different RES potentials studies available for Austria (Table 4). These studies vary in type (technical, reduced technical or economic-technical potential), in the energy carriers taken into account (e.g., geothermal energy, ambient heat, photovoltaics or solar thermal energy (ST)) and in their assumptions. Stanzer et al. [6] published data on technical potentials. Kaltschmitt and Streicher [70] introduced the terms of technical supply potential and technical demand potential. According to their definitions, supply potentials can be compared to technical potentials as used in [6]. [6] and Moser, Sejkora et al. [4] published reduced technical potentials (Table 4).

Table 4. Austrian RES potential studies.

	Technical Potential in TWh/a	Reduced Technical Potential in TWh/a	Economic-Technical Potential in TWh/a
Stanzer et al. [6]	607	357	–
Kaltschmitt and Streicher [70]	266 to 536	–	–
Winkelmeier et al. [71] [1]	51	–	
Pöyry [72] [2]	75	–	56
Moser, Sejkora et al. [4]	–	219	–
Brauner [73]	–	–	100

[1] only wind power energy potentials are analyzed, [2] only hydro power energy potentials are analyzed.

Some studies only focused on potentials for one renewable energy carrier such as Pöyry [72] on hydro power energy potentials or Winkelmeier et al. [71] on wind power energy potentials. The maximum of attainable wind potential, which was calculated by Winkelmeier et al. [71], can be compared to technical potentials. Pöyry [72] released data on technical and economic-technical potentials of hydro power. The results of [72] were also used as a reference in other studies mentioned (e.g., [70]).

As this work is based on technical potentials, only these are discussed in the following section. Depending on differences in technical assumptions (e.g., different collector types), Kaltschmitt and Streicher [70] calculated different technical potentials for PV, ST and ambient heat, which led to a large value range in total RES potentials of 266 to 536 TWh/a. Since multiple variants for the use of RES are possible (e.g., ST collectors vs. PV collectors on the same area, ST/PV collectors vs. areas for biomass on currently unused land) the term competition of energy technologies is introduced. Therefore, they published two versions of the data, one of which also considers competition between different energy technologies. The value deviation between these versions is about 10%. Stanzer et al. [6] published a total RES potential of 607 TWh/a. They did consider competition for area between energetic and non-energetic forms of use (e.g., use of arable land for biomass or food and feed production) but did not take into account competition of energy technologies (e.g., ST vs. PV).

There is a big range of the potentials presented because the technologies (e.g., collector types) considered and the assumptions regarding areas for renewable energy generation (exploitable areas) vary.

4. Methodology

In general, the goal of any national energy system is the provision of useful energy (e.g., mechanical work, heat) to meet human needs (e.g., movement, comfortable room temperature). To satisfy these energy service needs, each final energy application consumes final energy to provide useful energy. The final energy consumption can be covered by the utilization of primary or secondary energy carriers. As mentioned before (Section 2.2), primary energy carriers are those energy carriers that can be found as natural resources (e.g., coal) whereas secondary energy carriers (e.g., electricity) are provided by the conversion of primary energy carriers. Internal losses occur when converting primary energy carriers to secondary energy carriers, during transport to the final energy application and in the final energy application itself (Figure 5).

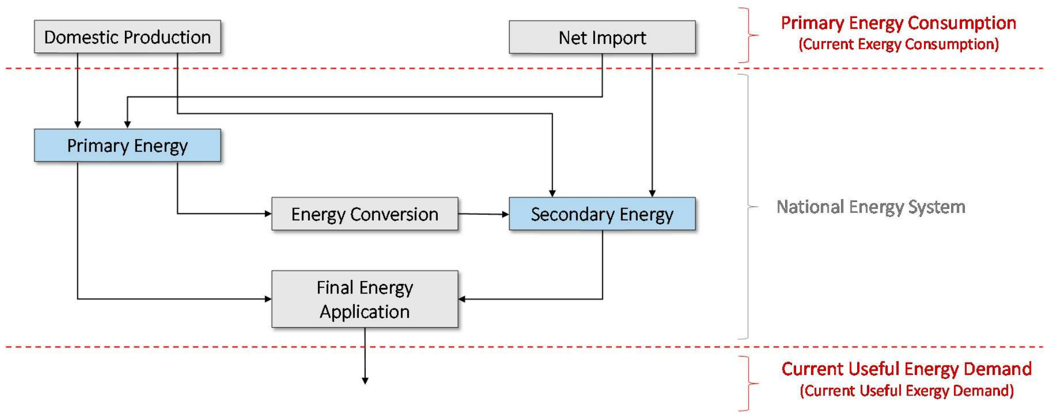

Figure 5. Schematic visualization of a general national energy system, including the energy flows into and out of the system (red). All energy flows into the system are called primary energy consumption. The flow out of the system is the current useful energy demand.

In this paper, a national energy system is analyzed. First, the system boundaries must be specified, as shown in Figure 5. Accordingly, the energy flows into and out of the national energy system are determined first and evaluated exergetically afterward.

On the basis of a national energy system, as shown in Figure 5, three exergy amounts can be determined. For this purpose, the inputs on the one hand and the outputs of the energy system on the other hand are analyzed. These three quantities are determined and then compared with each other in order to make statements about the analyzed energy system:

- **Current exergy consumption.** First, the total of energy that flows into the system is considered. This takes all energy for energy purposes which is used directly (without conversion processes) or indirectly (with conversion processes) by the energy system into account, including all mentioned internal losses. The energy that flows into the system is defined as primary energy consumption [14,49] (Figure 5). According to the IEA guidelines, the primary energy consumption of one country is the sum of domestic primary energy production (e.g., oil extraction, woody biomass production), domestic secondary energy production (e.g., electricity from photovoltaics), net imported (net import describes the difference between import and export) primary energy (e.g., sectors natural gas import) and net imported secondary energy (e.g., electricity import). In addition, stock changes of primary and secondary energy are also included. [13,14]. The primary energy consumption is used to determine the current exergy consumption, which is the first of the three exergy amounts.

- **Current useful exergy demand.** Next, the flow of useful energy out of the national energy system is balanced (Figure 5). It is the second of the three exergy amounts of this paper. The result of the exergetic analysis of the useful energy is called current useful exergy demand. It describes how much exergy is actually necessary to satisfy all energy service needs of one country. An energy service, and therefore the current useful exergy demand, is technology independent. An example is the provision of hot water, which can be provided by a heat pump or by a gas boiler.
- **Technical exergy potentials of RES.** Domestic production also includes the generation of local RES. This will play an important role in future national energy systems (e.g., [74]). Therefore, in addition to the analysis of the energy and exergy consumption of the current energy system, this paper also considers the technical potentials of RES. This can also be seen as an energy flow into the system. The exergetic analysis of the technical potentials of RES results in the third of the three exergy amounts of this paper. It indicates the maximum of exergy, which can be generated per year in a certain area, using the latest available technologies and without changing any structures such as land use. Other aspects such as economic efficiency, different paths of utilization, feasibility or social aspects are not considered.

According to the IEA guidelines, this paper considers the potentials of RES in the first multiple usable energy carrier. Therefore, some renewable energy sources are considered primary energy (e.g., woody biomass) and others secondary energy (e.g., electricity from photovoltaics, biogas from sewage sludge). The technical potentials of RES are first energetically calculated and afterward exergetically assessed in order to determine a technical exergy potential of RES of one country.

As mentioned in the introduction, first, the three basic exergy amounts are explained and determined in detail: current exergy consumption (Sections 4.1 and 4.2, since the current exergy consumption is based on primary energy consumption, which is explained in Section 4.1), current useful exergy demand (Section 4.3) and the technical exergy potentials of RES (Section 4.4). Then, these three exergy amounts are compared to each other in the results section to obtain the following findings (Figure 6):

- **Comparison of current exergy consumption and the current useful exergy demand to** determine the exergetic efficiency of the currently used energy system
- **Comparison of current exergy consumption and the technical exergy potential of RES** to show if renewable self-sufficiency is possible by expanding renewable production only
- **Comparison of the current useful exergy demand and the technical exergy potential of RES** to show how much renewable production is necessary to achieve renewable self-sufficiency in a system with maximum exergy efficiency.

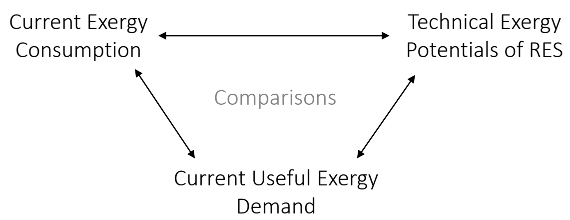

Figure 6. Overview of all comparisons, which are discussed in this paper, visualized by arrows.

The methodology of this work is explained using the example of Austria. Thus, this study presents a comprehensive analysis of the situation in Austria. All comparisons are carried out Austria-wide and spatially resolved. Therefore, in addition to overall statements about Austria, spatially resolved conclusions such as the under- or over-coverage of one individual district can be made. Section 4.5 shows how this methodology and therefore the whole analysis can also be adapted for other countries while the results of all comparisons are shown and discussed in the Sections 5 and 6.

4.1. Spatially Resolved Primary Energy Consumption

In order to enable a comprehensive description and analysis of the Austrian energy system, the PEC was used as the basis for the determination of the first of three exergy amounts: the current exergy consumption.

The definition of the PEC includes all losses (e.g., conversion losses, transport losses) which take place within the national energy system. Therefore, all losses that do not take place within the national energy system e.g., due to imports of secondary energy, are consequently excluded (Section 2.3). [14,17]

In order to enable a spatial segmentation, the PEC needs to be divided into different sectors, such as industry, transport, residential, and others. It must be mentioned that most sectors consume both primary energy (e.g., coal) and secondary energy (e.g., district heating or electricity). Therefore, the conversion losses of energy supply, which occur when providing secondary energy, the transport losses as well as the energy consumption for providing energy (e.g., on-site power of power plants) must be allocated to their respective sector. This allocation is performed according to their amount of energy consumption. Thus, this approach is comparable with the "polluter pays" principle in the field of environmental protection. In this paper, this Proportionally Allocated Consumption of the Energy Supply (PACS) only considered public infrastructure losses since the transformation losses (transformation input TI minus transformation output TO) of industrial conversion units such as company-owned plants (provision of heat and electricity), refineries (conversion of crude oil to various products), coke ovens (conversion of coal to coke) and blast furnaces (conversion of coke to blast furnace gas) are assigned to the corresponding industrial subsector directly. Most of these industrial transformation losses also have a corresponding industrial consumption of energy sector use (CES). The CES describes the energy consumption, which is necessary to enable the conversion process (e.g., the energy to run the coke oven at the necessary temperature).

Therefore, the primary energy consumption of the sector s can be expressed according to Equations (9)–(11). For each sector, it is the sum of the FEC, the CES, the transformation losses (TI-TO) and the PACS.

$$PEC_s = FEC_s + CES_s + PACS_s + TI_s - TO_s \tag{11}$$

PEC_s Primary energy consumption of sector s
FEC_s Final energy consumption of sector s
CES_s Consumption of energy sector use of sector s
$PACS_s$ Proportionally allocated energy consumption of the energy supply for sector s
TI_s Transformation input of sector s
TO_s Transformation output of sector s

The spatial segmentation of the primary energy consumption was performed individually for each sector. In general, a similar segmentation method is used for the industry, residential, public and private services sectors as well as agriculture and is based on segmentation factors such as inhabitants or number of people working in one specific industrial subsector per district. In order to enable spatial segmentation, the transport sector needs, in addition to segmentation factors (e.g., number of registered vehicles per district), information about the transport infrastructure, such as the length of motorways or rails per district. Due to the granularity of published data, it is not possible to achieve a higher spatial resolution of the primary energy consumption than the Austrian district level. Therefore, the Austrian political districts of 2016 are used. The spatial segmentation of the primary energy consumption per sector will be discussed in detail in Sections 4.1.1–4.1.3.

4.1.1. Industry

The industrial primary energy consumption were calculated using Equation (11). For this, the industrial transformation loss, which is the difference between transformation input and output, (e.g., company-owned power plants), the consumption of energy sector use (e.g., the energy necessary to enable the transformation processes in a blast furnace or coke oven), the industrial final energy consumption as well as the proportionally allocated energy consumption of the energy supply (e.g., caused by electricity drawn from the public grid) were taken into account (Table 5). The different terms of Equation (11) were determined using the energy balance statistics from Statistics Austria [2].

Table 5. Determination of the primary energy consumption for sector s = Industry, based on Equation (11).

Operator	Symbol	Explanation
+	CES_{Ind}	Consumption of energy sector use (coke ovens, blast furnaces, oil refineries)
+	FEC_{Ind}	Final energy consumption in manufacturing industries and construction
+	TI_{Ind}	Transformation input (coke ovens; blast furnaces; refineries; charcoal production; company-owned power, heating, and combined heat and power (CHP) plants)
−	TO_{Ind}	Transformation output (coke ovens; blast furnaces; refineries; charcoal production; company-owned power, heating, and CHP plants)
+	$PACS_{Ind}$	Proportionally allocated energy consumption of the energy supply
=	PEC_{Ind}	Industrial primary energy consumption

In order to enable the spatial separation of the industrial primary energy consumption, it was split into the different industrial subsectors (iron and steel, chemical and petrochemical, nonferrous metals, nonmetallic minerals, transport equipment, machinery, mining and quarrying, food, tobacco and beverages, pulp, paper and print, wood and wood products, construction, textiles and Leather, and non-specified industry. Classification by Statistics Austria [2]) in a first step. To perform this split, each mathematical term of Equation (11) and Table 5 was divided into different subsectors. A detailed breakdown of how this split was made can be found in Appendix A (Table A1).

Using published energy balances statistics according to international IEA standards e.g., from Statistics Austria [2], this split was easy for most of the mathematical terms, since the final energy consumption is published for each subsector. Furthermore, coke ovens and blast furnaces are allocated to iron and steel, refineries to chemical and petrochemical as well as charcoal production to non specified industry. Only some transformation inputs and outputs of company-owned power, heating, and CHP plants are not obvious to allocate since transformation inputs and outputs are not published per subsector. However, some transformation inputs and outputs can be assigned by contextual considerations (e.g., utilization of blast furnace gas can be directly allocated to the iron and steel subsector or black liquor to the pulp, paper and print subsector), but not all. For example, the natural gas-fired company-owned CHP plants are used in several subsectors, such as iron and steel, chemical and petrochemical or food, tobacco and beverages. We were not able to allocate these and similar transformation inputs which are natural gas, industrial waste, non-renewable municipal waste, renewable municipal waste, landfill gas, sewage sludge gas, other biogas and hydro power (in total approx. 8% of all industrial transformation inputs). We estimated them based on a literature review, which had its focus on production processes and energy consumptions of Austrian companies. Therefore, all publicly available information, such as sustainability reports and statistics, were used, in order to make the allocation as reasonable as possible. All details for the calculation of the industrial subsector resolved energy consumption are given in Appendix A (Table A1). This table includes everything but PACS, since the allocation of PACS is performed proportional based on the total fossil consumption and the total electricity drawn from the public grid per industrial subsector from Table A1. Then, after also adding PACS, the subsector resolved industrial primary energy consumption was determined. Based on this, in the second step, a spatial separation was accomplished. Therefore, a combination of a bottom-up with a top-down approach was used:

First, all publicly available energy demand data of industrial sites was used in a bottom-up approach. These energy demands can be primarily found on companies' websites as well as in their sustainability reports. Sustainability reports contain information on sustainable issues [75], such as waste treatment, energy consumption or accidents at work. Based on sustainability reports [76–111] the bottom-up based primary energy consumption for each industrial subsector and district was determined. With this approach, about 40% of the total industrial primary energy consumption was allocated, mostly for large industrial companies and their respective sites. Since these reports were published by the companies themselves, there are no statistical uncertainties and no errors in localization to be expected.

Next, the rest of the industrial primary energy consumption was allocated using a top-down approach. The fundamental assumption was that there is a linear relation between the primary energy consumption of the considered subsector and the respective numbers of employees. Based on the published employment data, the coefficient of this linear relation can be calculated for each industrial subsector and province of Austria. The combination of the corresponding coefficient and the numbers of employees was used to estimate the top down based primary energy consumption of one district (used data: [112]).

Finally, the sum of the bottom-up and the top-down based PEC was used to describe the total industrial PEC per district.

4.1.2. Residential Sector, Agriculture, and Commercial and Public Services

Determining the spatially resolved primary energy consumption of the residential sector, agriculture, as well as commercial and public services, is much easier than determining that of the industrial sector, since these three sectors all have no transformation input, no transformation output and no consumption of energy sector use. Therefore, the PEC for each of these three sectors is just the sum of the corresponding FEC plus the corresponding PACS (Equation (11)).

In this section, these three sectors are discussed combined, since the same methodology for calculating the spatial distribution of the PEC is used for all of them. This methodology is also similar to the top-down approach we used for the spatial segmentation of the industrial sector (Section 4.1.1). As explained in the previous section, the fundamental assumption for the two sectors, agriculture as well as commercial and public services, is a linear relation between the number of employees and PEC in one sector (used data: [2,112,113]). For the residual sector, the number of inhabitants and the residential PEC was used (used data: [114]). These assumptions enabled the determination of the PEC for the residential sector and agriculture, as well as commercial and public services per district in Austria.

4.1.3. Transport

The transport sector includes overland transport (primarily passenger cars and trucks), railways, inland navigation, aviation, and long-distance pipelines. The PEC of the transport sector is equal to the sum of FEC and PACS (Equation (11)). PACS must consider the relevant energy carriers per sector. In the transport sector, these are liquid fuels like gasoline, diesel or kerosene, but also electricity and natural gas. Since the conversion losses for the provision of liquid fuels are taking place in the refinery and the refinery is per definition allocated to the industry (Section 4.1.1), PACS in the transport sector only takes electricity as well as natural gas for long distance pipelines into account.

In this work, we tried to allocate the energy consumption of the transport sector to the location of its actual usage. Based on the published data alone, this was not always possible. Therefore, assumptions and simplifications were necessary:

The allocation of private passenger cars' energy consumption was based on statistics about kilometres driven and fuel consumption of private cars by Statistics Austria [115]. There, the total final energy consumption of private cars is published per province. If it is assumed that private car traffic mainly takes place in the district in which the vehicle is registered, the final energy consumption can be split up between the different districts by the number of registered vehicles (used data: [116]). This assumption is based on the fact that the average mileage per private car in Austria is 31 km per day in 2017/2018 [115].

Trucks can be divided into two groups. On one side, there are trucks which are only used locally. These local trucks are only used for short distances, starting and stopping every day at the same point—34% of all distances driven during domestic transports are shorter than 50 km [117] This statistic includes only domestic transports which are operated by trucks registered in Austria [117]. This is justified as 99.3% of the total transport volume up to 49 km is carried out by trucks registered in Austria [118]. Through the total number of kilometres driven for short domestic transports (less than 50 km), which is available per province, and the average consumption of a truck (29.1 l Diesel per 100 km [119]), the total FEC of these local trucks can be estimated on a provincial level. It was assumed that the consumption of these local trucks primarily occurs where the truck is registered due to the short transport distances. Therefore, the spatial separation was based on the number of registered trucks per district [116].

The final energy consumption of the remaining overland transport was calculated by the difference between the total overland transport per province [113] and the already allocated consumption of private passenger cars and local trucks. This includes business passenger cars and trans-regional trucks and mainly takes place on motorways and expressways. In order to take this into account, a spatial separation was performed by the length of motorways and expressways per district. The length, as well as the position of the Austrian motorway and expressway infrastructure, was extracted from OpenStreetMap (OSM). OpenStreetMap is a collaborative project, which collects and structures geographic data, such as buildings, paths, streets, rivers or forests [120].

The methodology used for the spatial separation of the remaining overland transport was also used for railways, inland navigation and long-distance pipelines. Therefore, the final energy consumption per province for the mentioned applications [113] was spatially separated by the length of the rail infrastructure as well as by the length of the Danube. Only the Danube was taken into account, as it is the only international waterway in Austria which is relevant for the transport of goods [121,122]. The Danube is part of a European waterway which connects the North Sea with the Black Sea. The length of the rail infrastructure and the length of the Danube have both been extracted from OSM. The published data from GSV—Austrian Association for Transport and Infrastructure—were used for the length and position of the long-distance oil and natural gas pipelines [123].

For each of these considered applications, a specific FEC per kilometer of infrastructure or waterway was calculated. Thus, the FEC is distributed evenly rather than taking the actual average traffic load per km into account. This assumption had to be made since there are no traffic flow data of Austria published. However, based on the available data, at least a simplified weighting can be achieved. For example, important railway lines such as the Western Railway ("Westbahn") in Austria usually have two or four parallel rails. Thus, in the calculation, these railway lines were weighted two or four times in comparison to a single-rail section of a side line. This principle was also applied to the calculation of the remaining overland transport based on the number of motorway and expressway lanes as well as to the calculation of the long-distance pipelines based on the number of parallel pipes.

Contrary to the principle of determining consumption where it actually occurs, the FECs of aviation were allocated to the airports, since there are no data available which would enable a spatial separation. The FECs are published for each province of Austria [113]. Since there is not more than one airport with considerable fuel consumption and well-known location per province, no calculations for the spatial separation are necessary.

In order to calculate PEC of the transport sector, we just added PACS proportionally to the FEC, based on the actual electricity and natural gas consumption.

4.2. Spatially Resolved Current Exergy Consumption

Based on the previously calculated spatially and sectorial resolved PEC, we calculated the first of the three exergy amounts, the current exergy consumption. This describes how much exergy is currently consumed in Austria per year, without considering any efficiencies or any possible improvements. Therefore, it represents the status quo. It can easily be calculated by multiplying the spatially resolved primary energy demand per energy carrier by the exergy factors per energy carrier (Section 2.1). For chemical energy carriers such as natural gas or gasoline, an exergy factor of 1 is assumed.

4.3. Spatially Resolved Current Useful Exergy Demand

In contrast to the current exergy consumption, the current useful exergy demand, which is the second of the three exergy amounts of this paper, does not take exergetic losses (e.g., conversion losses, transport losses, losses of the final energy application) into account. It is the exergetic assessment of the useful energy demand and describes how much exergy is actually needed to satisfy the energy service needs. Since it only describes how much exergy is needed, it is independent of the technology.

An example for such an energy service is the provision of hot water in residential buildings. Here, hot water is already the useful energy type. If we assume that the hot water service is provided by natural gas, the exergy consumption is nearly equal to the natural gas consumption, since the exergy factor of natural gas is approximately 1 (Section 2.1). However, the useful exergy demand is much lower than the exergy consumption. It can be calculated by multiplying the natural gas demand by the Carnot Factor, which is around 13%. The Carnot Factor is depending on the temperature of the hot water as well as the surrounding temperature. In this example a hot water temperature of 65 °C and a surrounding temperature of 20 °C is assumed.

Therefore, while the current exergy consumption is based on the primary energy consumption (Section 4.2) the current useful exergy demand is only based on the useful energy demand (Figure 5).

In addition to final energy applications, the useful energy demand must also include the CES (coke ovens, blast furnaces, oil refineries), since they consider the energy needed to run the corresponding processes (e.g., the blast furnace) [49]. The determination of the spatially resolved current useful exergy demand will be discussed for each sector in the following Sections (Sections 4.3.1 and 4.3.2).

4.3.1. Industry, Residential Sector, Agriculture as well as Commercial and Public Services

As mentioned in the previous Section, only the final energy consumption, as well as the consumption of energy sector use, are used to determine the current useful exergy demand. Since in Sections 4.1.1 and 4.1.2 each term of Equation (11) has been determined for each sector, the calculation of the spatially resolved current useful exergy demand was performed directly on these data. Furthermore, the useful energy analysis, provided by Statistics Austria [113] includes additional information about the applications of the energy use, e.g., for industrial furnaces, for stationary engines or for lighting, and information and communications technology (ICT). In this section, the current useful exergy demand is always calculated with the useful energy multiplied by the exergetic efficiency of the process. The required exergetic efficiencies can be found in Section 3.1.3. If an efficiency range instead of a single value is specified, the mean value is taken.

To determine the current useful exergy demand, a basic distinction must be made between heating and cooling applications (space heating and air condition, vapor production as well as industrial furnaces), stationary engines as well as electricity for lighting, ICT and electrochemical purposes.

The exergetic assessment of heating and cooling application was based on the actual necessary temperature levels of the energy utilization. For this purpose, a breakdown (combination of [113,124,125];

commercial and public services as well as agriculture are estimated) was used which described how much of the process heat demand per sector (or industrial subsector) takes place at which temperature level (Appendix A Tables A2 and A3). By multiplying these data by the (sub-) sector resolved total final energy demand of process heat (vapor production, industrial furnaces as well as the three industrial consumptions of energy sector use coke oven, blast furnace and refinery), the process heat demand per temperature level can be calculated for each sector and each industrial subsector. In addition to the process heat demand, the energy demand for space heating and air conditions per sector or per industrial subsector can directly be used, since it is published separately. The total exergy demand for heat and cooling applications per sector and per industrial subsector can be calculated by multiplying the energy demand per temperature level with their corresponding Carnot Factor (Appendix A Table A3).

The electricity demand for heating and cooling applications also includes the required energy for the operation of heat pumps and chillers. Since they need pure exergy (mechanical energy) for increasing the temperature level of a heat flow, it does not make sense to assess the electricity demand according to temperature level. Thus, the electricity demand for heating and cooling applications is defined as 100% of exergy.

In Section 3.1.3, the exergetic efficiency of stationary engines and lighting is presented. The exergetic efficiency of stationary electric engines is about 50% and, for diesel- or natural gas-fired stationary engines, it is between 42% and 50%. For lighting, the exergetic efficiency is between 12% (Halogen) and 49% (LED). Due to the big efficiency range of the various lighting technologies, the actual share of these technologies is crucial. In 2017, the commercial and public services sector in Germany had the following breakdown of the various lighting technologies, based on the energy consumption: 58% fluorescent tubes, 16% sodium-vapor lamps (sodium-vapor lamps have a comparable efficiency as LEDs, based on the luminous flux per watt [126]), 14% halogen and light bulbs, and 12% LEDs [127]. We assume that a similar breakdown holds for Austria across all sectors.

The useful energy analysis for Austria [113] distinguishes only between lighting and ICT in the residential sector. For the other sectors, the electricity demand for lighting and ICT is combined. In industry, as well as commercial and public services, 50% and 69%, respectively, of the combined electricity demand for lighting and ICT is used for lighting [127,128]. Due to the lack of available data for agriculture, the same values as for commercial and public services were used.

The exergetic efficiency of ICT and electrochemical purposes was estimated at 100%, as the exergy is directly consumed by the service (ICT) or by the product (electrochemical purpose) since there is no conversion from final energy to useful energy.

However, the methodology for the spatial segmentation based on the combination of the top-down and bottom-up approach could not be used—the sustainability reports, which are used for the bottom-up approach, do not specify different types of energy usage. Generally, these reports include only the purchased amount of energy per year. Due to this lack of data, the spatial segmentation of the current useful exergy demand was only based on a top-down approach.

4.3.2. Transport

The determination of the exergetic efficiency of the transport is based on Section 3.1.3. Therefore, for Austria, the average driven distance weighted exergy efficiency of the road-based traffic is 27%. This value takes different types of cars, trucks and motorcycles into account. The exergetic efficiency of other fossil fuel-based vehicles are comparable.

In the useful energy statistics, supra-regional and international transports in pipelines are also allocated to the transport sector. The exergetic efficiency of gas pipelines can be calculated by the efficiency of the compressor (75% to 84%) and the efficiency of a gas turbine (28 to 35%). The gas turbine must only be considered if the natural gas from the pipeline is directly used to run the compressor.

For the calculation of the current useful exergy demand in the transport sector, the spatially resolved final energy demand (Section 4.1.3) was multiplied by the exergetic efficiency, as explained before. If an efficiency range is specified instead of a single value, always about the mean value is taken.

4.4. Spatially Resolved Technical Potential of Renewable Energy Sources

In this section, we discuss the determination of a spatially resolved renewable potential of Austria. This is the last of the three exergy amounts. This analysis is based on previous research [4,129,130] and has been further developed with the focus on an increase in spatial resolution. In this study, the renewable potential for each municipality in Austria is determined.

This paper covers the following renewable energy sources: solar thermal systems, photovoltaic, different forms of biomass, wind power, hydro power, geothermal energy and ambient heat. However, due to the exergetic focus of this paper, some energy sources were excluded:

- Ambient heat, which might be used in other studies, cannot be considered since per definition it has no exergy content.
- An exergetic comparison between solar thermal systems and photovoltaics showed that photovoltaics has an exergy output that is higher than the one of solar thermal systems, even if the energy output of solar thermal is 4 to 5 times higher: The total system efficiency of modern photovoltaics is about 16% to 17% [131], which is equal to the exergetic efficiency since electricity has an exergy factor of 1. In contrast, a solar thermal system with a high efficiency of 80%, hot water temperature of 75 °C and a surrounding temperature of 10 °C has an average exergetic efficiency of 15%. Therefore, in this study, only photovoltaics were considered. In addition to the higher efficiency, electricity has additional benefits as it is easier to transport and can be used for various applications.
- The geothermal energy potential was not considered in this paper since most of the geothermal potential has a low exergy content due to the low temperature difference to ambient heat, where a heat pump is necessary to make the heat accessible (comparable to ambient heat as a potential). Geothermal potentials with higher temperatures were also not considered in this study due to the low potential. In 2050, the extended potential of geothermal energy in Austria is estimated as 3062 GWh/a [132], which is equivalent to an exergy potential of less than 1 TWh/a and therefore, will not change the overall result (assumed temperature of the hot water is 150 °C since in Austria the highest water temperature of a geothermal application is in Bad Blumau with 143 °C [132]).

Since some renewable energy carriers are difficult to utilize (e.g., sewage sludge has a very low dry matter content), they are not balanced until they are converted into a generally usable energy carrier (e.g., conversion of sewage sludge to biogas). This corresponds to the IEA guidelines. Therefore, all considered renewable energy carriers (e.g., electricity, biogas, wood) have an exergy content of 100%.

Since there are different types of potentials, it is important to clarify that all potentials shown in this study are technical potentials. The definition of technical potential is discussed in Section 3.3. Technical potentials in general, and for the purpose of this study, do not differentiate between currently utilized or currently not utilized potentials.

4.4.1. Photovoltaic

The most important influence for the determination of a spatially resolved photovoltaic potential are the usable areas. Usable areas are orientated southwards with as little shading as possible. For example, these areas may be grassland, arable land, building facades or roofs. The energy output of a photovoltaic cell scales linearly with the area. In this work, only rooftops and fallow land, including currently unused agricultural areas, were considered.

The spatially resolved PV potential of rooftops is based on the publicly available data provided by OSM. OSM includes the positions as well as the floor area of over 85% of all buildings in Austria, which means that this data set can be considered as nearly complete [133].

The combination of the spatially resolved building data from OSM and the solar rooftop cadaster of the Austrian province Styria [134] allows the determination of the spatially resolved PV rooftop potential. This cadaster is provided by the Styrian government and describes the PV potential of each rooftop in Styria. It considers orientation and tilt of the rooftop but also shading [135]. An analysis of the combination of the OSM data and the solar rooftop cadaster of Styria showed that there is a linear relation between the sum of all floor areas and the sum of all PV potentials per municipality (coefficient of determination of this linear regression is $R^2 = 0.86$). Graz was not included in this linear relation since it is one order of magnitude bigger in terms of inhabitants than all the other municipalities of Styria [136].

To compensate for the lack of data of PV rooftop potential on a national level, the following assumptions were made in order to extrapolate the PV potential for each municipality in Austria based on the total sum of floor areas:

- For municipalities with up to 100,000 inhabitants, the factor from the linear correlation is used.
- For municipalities with 100,000 up to 300,000 inhabitants, the specific value of Graz is used.
- For Vienna, the officially published PV potential is used [137].

In this paper, the following types of land use were considered unused land (based on [138–140]): meadows yielding only one crop of hay per year, common pastures, bedding meadows, grasslands where the formation of steppe, woodland and scrub is prevented and no agricultural use is made, and land no longer farmed/unused greenland. Based on this definition, the spatially resolved PV potential of unused land can be determined by the area of unused land per municipality and a mean value of 8.9 acres/MW_{ac} (approx. 36,017 m^2/MW_{ac}) [141]. In this calculation, it was assumed that only 50% of the total unused land can be used for PV due to shading [4]. In all PV relevant calculations, and that the annual PV full load hours were considered with 1000 [142,143].

4.4.2. Biomass

Biomass has various well-known paths of use. However, there are also applications in which the direct use of biomass is not possible (e.g., as fuel for a car). In these cases, the biomass has to be converted to a secondary energy carrier, such as biogas or biofuel to make usage possible. There are three different ways of converting biomass: thermo-chemical conversion (e.g., gasification of biomass), physical-chemical conversion (e.g., production of vegetable oil) and biochemical conversion (e.g., fermentation of biomass to biogas) [144].

In this work, different types of biomass potentials were considered: wood, wood products and wood waste, black liquor, biogas from various biogenic waste as well as fuels from field crops. Wood, wood products and black liquor were taken into account directly, without any conversion, since they can be utilized directly in furnaces. The exergy potential was calculated by multiplying the amount in tons per year with its higher heating value.

The spatial segmentation in this section was done as before: the total potential (for some biomasses available per province, for some only on a national level) of each biomass was allocated to the individual municipalities by a factor. This factor might be the number of inhabitants per municipality, the total area of the municipality, or the number of people working in a specific sector per municipality. As an example, to calculate the wood waste potential per municipality, the total potential of wood waste was divided by the total number of people working in the wood processing industry nation-wide and multiplied by the number of people working in this industry sector in the specific municipality.

The amount of wood, wood products, wood waste, and black liquor is available per province was spatially resolved by using the forest area, the number of people working in the wood processing industry as well as the number of people working in the pulp and paper industry per municipality (Table 6).

Table 6. Considered wood, wood products, wood waste, and black liquor.

Type	Amount	Higher Heating Value	Spatial Segmentation
Forest (currently unused) [1]	3.48 million m^3/a [2] [145]	2696 kWh/m^3 [3]	forest area
Firewood and wooden pellets	18,482 GWh/a [2]	–	forest area
Wood waste	23,767 GWh/a [2]	–	numbers of people working in the wood processing industry
Black liquor	9073 GWh/a [2]	–	number of people working in the pulp and paper industry

[1] Difference between forest growth and forest use, [2] calculated with 20% crop losses [144,146], [3] calculated with the actual share of the different tree species in Austria [145] and the higher heating value (water content 0%) as well as the specific density for each tree species [144].

The potential of each type of biogenic waste was calculated by the amount of waste multiplied by the specific gas yield. Since the total amount of farm manure and sewage sludge in tons per year is unknown, the methane potential was calculated by the gas yield per animal or per population equivalent and the number of animals or the number of population equivalent, respectively. All other waste types are published in tons per year. In some cases, these amounts of waste are available for each province, in the other cases, they are only available on a national level. In order to ensure the best possible accuracy, the amount of waste per province was used wherever possible. The factor for the spatial segmentation is specific for each type of waste (Tables 7 and 8).

Table 7. Considered types of biogenic waste.

Type	Amount in t/a	Specific Gas Yield in Nm^3 CH_4/t Fresh Mass	Availability of Data	Spatial Segmentation
bio waste	530,700 [147]	103 [148]	Province	inhabitants
garden waste	482,800 [147]	64 [149]	Province	area
organic in residual waste	1,437,000 [1] [147]	103 [148]	Province	inhabitants
public green waste	472,000 [147]	64 [149]	Austria	area
private composting	1,500,000 [147]	64 [149]	Austria	area
kitchen and food waste	113,400 [147]	205 [2] [150]	Austria	inhabitants
cereal straw	2,526,326 [3]	153 [150]	Austria	cereal acreage
corn straw	2,208,831 [4]	82 [150]	Austria	corn acreage
rapeseed straw	162,959 [5]	97 [150]	Austria	rapeseed acreage
sugar beet leaf	6,713,538 [6]	47 [150]	Austria	sugar beet acreage

[1] Only 17.81% of this total amount of residual waste is organic [147], [2] mean value of old bread, baking waste, cheese waste and food waste with a different share of fat, [3] calculated with a mean yield of 450 t cereal per km^2 [151], the total cereal acreage of 6122 km^2 [139] and a mean fruit-straw-ratio of 0.917 [144], [4] calculated with a mean yield of 1090 t corn per km^2 [151], the total corn acreage of 2026 km^2 [139] and a fruit-straw-ratio of 1 [144], [5] calculated with a mean yield of 280 t rapeseed per km^2 [151], the total rapeseed acreage of 540 km^2 [139] and a mean fruit-straw-ratio of 2.8 [144], [6] calculated with a mean yield of 7320 t sugar beet per km^2 [151], the total sugar beet acreage of 448 km^2 [139] and a mean fruit-straw-ratio of 1.7 [144].

Table 8. Considered sewage sludge and animal excrements as biogas potential. All values are only published for the whole of Austria.

Type	Amount	Specific Gas Yield	Spatial Segmentation
sewage sludge	14,209,529 PE_{60} [1] [152]	14.5 Nm^3 $CH_4/(PE_{60}*d)$ [2]	inhabitants
dairy cows	7,669,671 [153]	290 Nm^3 CH_4/(animal*a) [3] [154]	number dairy cows
fattening pigs	6,632,840 [153]	21 Nm^3 CH_4/(animal*a) [3] [154]	number fattening pigs
beef cattle	2,355,874 [153]	129 Nm^3 CH_4/(animal*a) [3] [154]	number beef cattle
chicken	86,775 [153]	1.4 Nm^3 CH_4/(animal*a) [3] [154,155]	number chickens

[1] The number of population equivalent 60 (PE_{60}) measures the pollution load in waste water. The average pollution load of one person in 24 h defines one population equivalent, [2] calculated with an average value of 25 l biogas per PE_{60} and day [156] as well as with the lower heating value of the biogas of 6.4 kWh/Nm^3 [157], [3] calculated with the amount of excrement per animal and year as well as the specific gas yield.

In Austria, the biogas potential of waste from the food and beverage industry is 152 million Nm^3 CH_4/a [130]. A spatial segmentation was achieved by the number of people working in the food and beverage industry per municipality.

Apart from different forms of wood, biogenic waste and farm manure, black liquor as well as sewage sludge, this study also takes the current Austrian production of biodiesel, bioethanol and biogas into account. Only the production of Austrian biomass for the Austrian market was considered. To avoid a competitive situation with food and feed production, the currently used areas for fuel and biogas production are not expanded (Table 9).

Table 9. Current production of bio fuels and biogas using biomass from Austria.

Type	Amount	Spatial Segmentation
biodiesel from new oil	31,604 t/a [1] [158]	arable land
biodiesel from used cooking oil and other used fats	47,406 t/a [2] [158]	inhabitants
Bioethanol	185,669 t/a [158]	arable land
Biogas	967 GWh/a [3] [158]	arable land

[1] 40% of the total biodiesel production in Austria is based on new fruit or seed oil but only 26.8% of the total biomass input is biomass from Austria [158]. [2] 60% of the total biodiesel production in Austria is based on used cooking oil and other used fats but only 26.8% of the total biomass input is biomass from Austria [158]. [3] In 2017, biogas plants in Austria produced a total of 565 GWh of electricity (mean efficiency of power units: 36.5% [154]) and 149 GWh of gas were fed into the public gas grid [158].

In addition to the techniques mentioned above, the fermentation residue of the biogas plants can also be used to produce some additional methane. For this purpose, the fermentation residue must first be dried and then gasified and methanized. The waste heat generated in the gasification and methanation can be used for drying fermentation residue. Overall, with this process, another 0.22 GWh biogas can be produced from the fermentation residue of 1 GWh biogas [130].

4.4.3. Wind Power

The maximum for attainable wind potential in Austria is published in the study "Windatlas und Windpotentialstudie Österreich" [71,159]. This potential considers all reasonable positions in Austria and can be compared to the technical potential of the other renewable energy sources mentioned in this section. Since this study [71,159] only publishes the maximum of attainable wind potential per province, a methodology for spatial separation had to be applied.

In general, the wind potential of a certain region can be estimated based on a uniform dot matrix. Each point of this dot matrix represents one possible wind farm. First, the whole region will be covered by this dot matrix. In the second step, some dots will be eliminated from the matrix, according to well-defined rules, e.g., distance to buildings. Finally, the potential per dot can be estimated in combination with the annual average wind speed [160].

This methodology was used for the segmentation of the maximum of attainable wind potential per province of Austria broken down into municipalities. To achieve this, the number of wind-speed-weighted dots per municipality was calculated. Thus, the maximum for attainable wind potential per municipality in Austria was calculated from the ratio of the number of wind-speed-weighted dots per municipality and the total number of wind-speed-weighted dots per province. In this work, a minimal distance to buildings of 1000 m and a maximum height above sea level of 2000 m was used (spatially resolved sea level of Austria: [161], spatially resolved annual mean wind speed: [160]). Dots in nature reserves and national parks were also excluded (spatially resolved nature reserves and national parks: [162]).

4.4.4. Hydro Power

The hydro power potential was taken from the study "Wasserkraftpotenzialstudie Österreich Aktualisierung 2018". In this study, Pöyry Austria GmbH calculated the technical-economical potential, but also the technical hydro power potential of Austria. These potentials consider the flows of all rivers in Austria, their change in water level as well as in altitude. The technical potential assumes that 87% of the total flow potential can be harnessed. Since the spatially resolved technical potentials are only published in the form of a map, we analyzed this using the GIS application QGIS [163] and calibrated it based on Austria's total potential. Furthermore, we used QGIS to quantify the technical hydro power potential per municipality. [72]

4.5. Generalization of the Approach

This study used Austria as an example for presenting the methodology of calculating the three spatially resolved exergy amounts: the current exergy consumption, the current useful exergy demand and the technical exergy potentials of RES.

The methodology shown is general and can also be used for other countries since the necessary energy statistics (e.g., final energy consumption per sector, transformation inputs and outputs, transport losses, consumption of energy sector use, etc.) are also published by Eurostat [1] or other comparable national statistics services or agencies. If necessary, the data of comparable countries can also be used (e.g., share of different final energy applications).

The methodology for exergetic analysis for determining current exergy consumption and the current useful exergy demand can be applied to other countries directly and, if necessary, the exergetic efficiencies for different applications (e.g., efficiency of stationary motor system), which are listed in Section 3.1.3, can be used.

Especially when determining the national technical potential of RES or the spatial separation of the national results, the methodology has to be adapted to the given data (e.g., already published potential studies, statistical data on spatial distribution of land use). However, since the methodology is mainly based on our own calculations, the basic ideas can be used generically (e.g., the methodology of determining the PV potential using OSM, using spatial segmentation factors, etc.).

5. Results

In this section, the results of applying the developed methodology to Austria (Section 4) are shown. For the presentation of the results, we use the structure introduced in Section 1. The results of the three exergy amounts will be discussed in Section 5.1. Furthermore, the Austria-wide and spatially resolved comparisons of the three exergy amounts are presented in Sections 5.2 and 5.3, respectively.

5.1. Results per Exergy Amount

5.1.1. Current Exergy Consumption and Current Useful Exergy Demand

In this section, the results of the two exergy amounts, the current exergy consumption and the current useful exergy demand will be presented together, due to the comparable structure of the results. This leads to a clearer structure without repetitions. Please note, comparisons between these two exergy amounts are only made in Section 5.2.1 (Austria-wide) and in Section 5.3.1 (spatially resolved).

In accordance with the calculation shown in Section 4, the current exergy consumption in Austria amounts to 370 TWh/a, whereas the primary energy consumption amounts to 374 TWh/a. The calculated primary energy consumption (374 TWh/a) is slightly lower than the value reported by Statistics Austria for 2017 (381 TWh). The difference (less than 2%) is caused by the combination of bottom-up and top-down approaches and by various data sources from varying years.

The current exergy consumption is nearly equal to the calculated total primary energy consumption of Austria, since over 98% of the primary energy consumption of Austria is covered by high exergetic energy carriers (e.g., imported natural gas, electricity from photovoltaics or extracted crude oil). The remaining primary energy consumption is covered by energy carriers with a low exergy value (solar thermal energy) or no exergy content at all (ambient heat). The final energy demand of other low exergetic energy carriers (geothermal energy and reaction heat) as well as the transformation input of solar thermal and geothermal energy are neglectable, since they are in total being less than 0.1% of the primary energy consumption in 2017. According to the calculation in Section 4, the current useful exergy demand of all sectors amounts to 125 TWh/a, which is significantly lower than current exergy consumption.

For the spatially resolved visualization of the current exergy consumption and the current useful exergy usage, district resolved maps are used (Figures 7 and 8). In these maps, one can see the absolute exergy consumption or demand per district, represented by the size of the pie charts. In addition, the pie charts also illustrate how much exergy is needed in which sector. Since the absolute value per district is dependent on the respective district area, the relative consumption or the relative demand per district is represented by the gray scale. To calculate the relative consumption or relative demand per district, the current exergy consumption or the current useful exergy demand, respectively, is divided by the area. Please take note of the different scales of all maps. A spatial overview of all provinces and districts in Austria can be found in Appendix B (Figure A1).

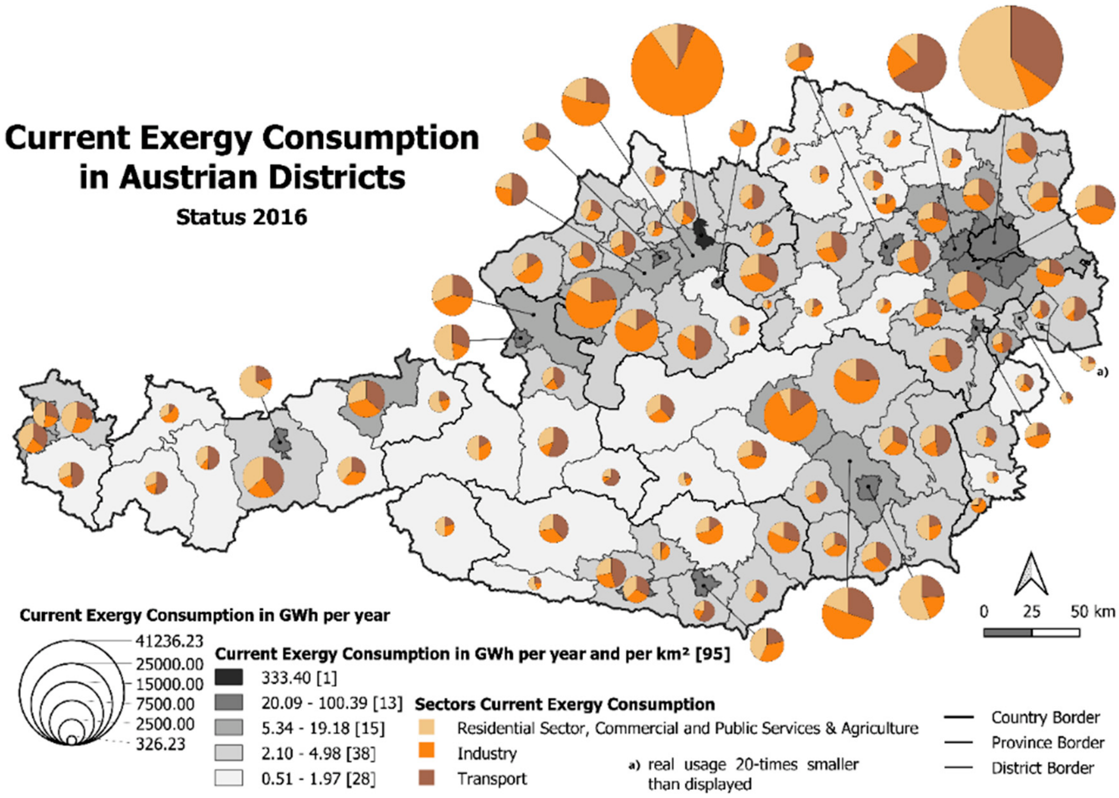

Figure 7. Current exergy consumption in Austrian districts. The absolute and relative consumption is represented by the size of the pie charts and by the gray scales, respectively. The maximum consumption can be found in industrial and urban areas (map source: Statistics Austria - data.statistik.gv.at).

In Austria, the maximal relative current exergy consumption and current useful exergy demand are located in urban areas. These are cities such as Vienna, Graz, Linz, Innsbruck or Klagenfurt, including their surroundings. In addition, industrial regions, e.g., Upper Austria, Lower Austria, and Styria, also have a high relative exergy consumption and demand. One can see that the absolute exergy usage and demand are highest in Vienna and Linz. In terms of absolute consumption and demand, these two cities are comparable, but the share of the sectors is very different.

The high relative exergy consumption in urban areas can be explained by the population density. For example, in Vienna, 35% of the current exergy consumption is caused by transport, 31% by the residential sector, 24% by commercial and public services and only 9% is caused by industry (agriculture in Vienna is neglectable). The fact that the city of Linz has an absolute exergy consumption comparable to Vienna, but has a very different share of the sectors, is due to a smaller population and a strong industrial sector. Linz only has around 11% of the population of Vienna [114] but has a strong energy intensive industry, such as an iron and steel mill with three blast furnaces. Therefore, in Linz, 84% of the current exergy consumption and 93% of the current useful exergy demand are caused by industry. In general, areas with a high share of energy intensive industry (industries which are obliged to participate in emission trading [164,165]) have a higher relative exergy consumption and a higher relative exergy demand.

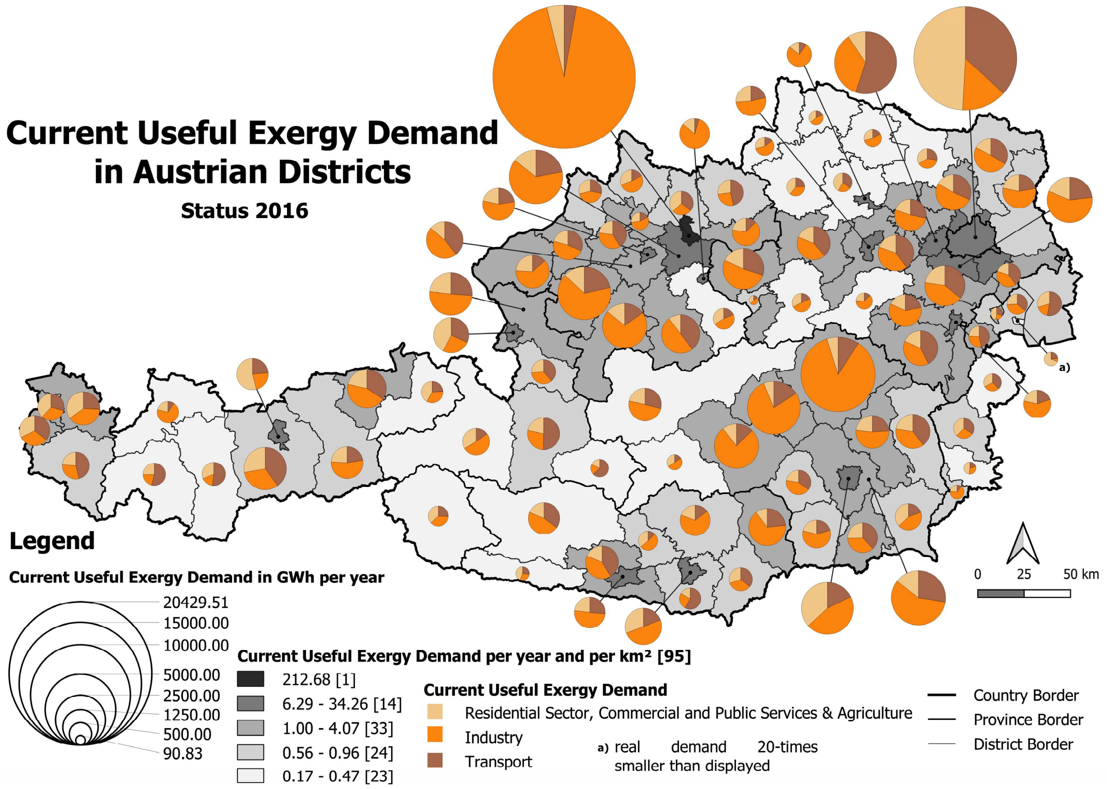

Figure 8. Current useful exergy demand in Austrian districts. The absolute and relative demand is represented by the size of the pie charts and by the gray scales, respectively. The maximum demands can be found in industrial and urban areas (map source: Statistics Austria - data.statistik.gv.at).

5.1.2. Technical Exergy Potentials of RES

In this section, the exergy potential of RES in Austria will be discussed. The exergy potential consists of hydro power (75 TWh/a), photovoltaics (54 TWh/a), woody biomass (52 TWh/a), wind power (51 TWh/a), biogas and biofuels (25 TWh/a), as well as black liquor (9 TWh/a). In total, the exergy potential amounts to 266 TWh per year. The spatially resolved potential for each district of Austria is shown in Figure 9. For simplicity, the potential is shown for each district, although it is calculated for each municipality of Austria individually. Since, per definition, all of the considered potentials of RES have an exergy content of 100% (Section 4.4), this exergy potential is equal to the primary energy potential of RES.

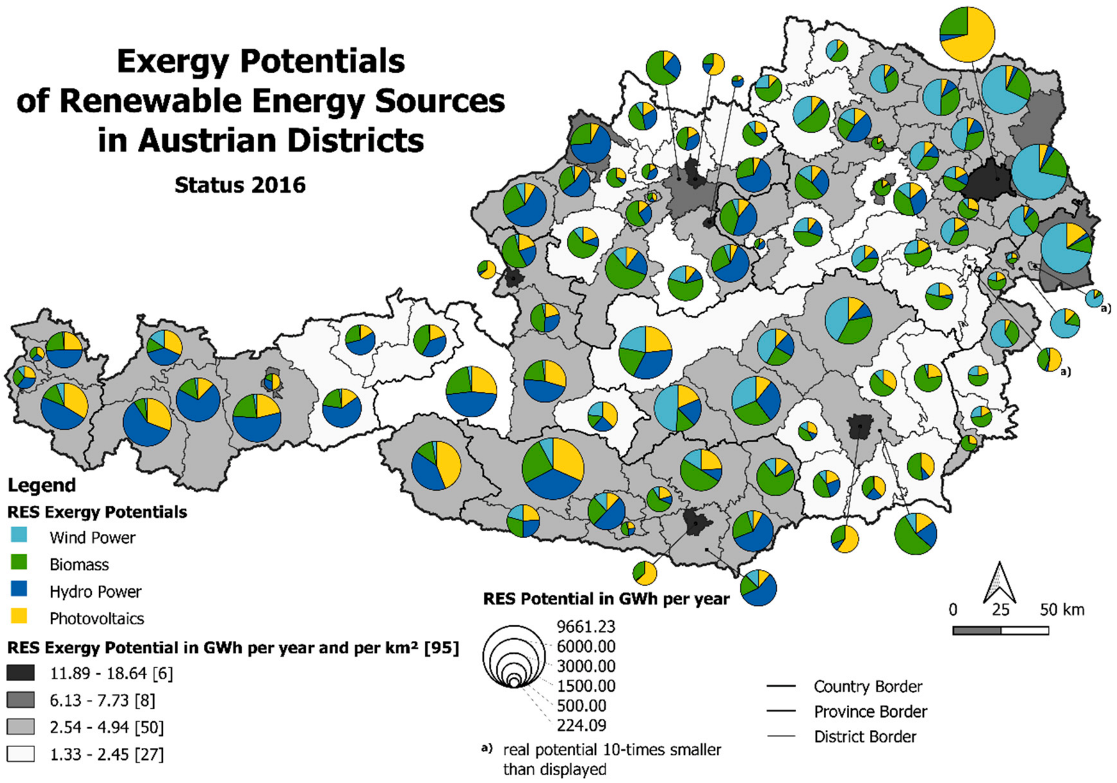

Figure 9. Exergy potential of RES in Austria per district. Apart from cities, the potential of RES is rather evenly distributed, even if the individual shares of the various RES per district vary (map source: Statistics Austria - data.statistik.gv.at).

Figure 9 contains a variety of information. The total technical exergy potential of RES per district is represented by the size of the pie chart. The slices of the pie chart show the share of different renewable energy sources per district. Additionally, the relative potential per district, which is the total potential divided by the area, is visualized by the different shades of gray. Please take note of the different scales of all maps. A spatial overview of all provinces and districts in Austria can be found in Appendix B (Figure A1).

In Figure 9, one can see that there are huge regional differences in the share of the different renewable energy sources. Urban regions tend to have a higher proportion of photovoltaics and biomass (e.g., cities such as Vienna, Graz, Linz, Salzburg) while wind power is most dominant in the north-east of Austria. There is a large share of hydro power in the west and south-west of Austria, but also along the rivers Danube and Inn. Apart from the share of the different energy sources, the relative exergy potential in Austria is relatively equally distributed (mean value: 4 GWh/(a·km^2), standard deviation: 3 GWh/(a·km^2)). Only seven districts have a higher potential than the average plus standard deviation (>7 GWh/(a·km^2)) and there are no districts that have a lower potential than mean value minus standard deviation (<1 GWh/(a·km^2)).

The share of PV and biomass in urban regions can be explained by the high number of rooftops, which can be used for photovoltaics, and the biomass potential in these areas is mainly based on the high population density: a high number of inhabitants cause a lot of organic waste (e.g., bio waste or food and kitchen waste as well as sewage-sludge) which can be utilized in biogas plants. However, rural regions also have photovoltaic (unused land) and biomass (agricultural, residuals, forests, wood waste and black liquor) potential. Therefore, every district of Austria offers photovoltaic and biomass potential, but the share varies strongly.

In Austria, the highest average wind speeds are found in the north-east, mainly due to the topography [160], resulting in comparatively high wind potentials in this area. The mountain area in the west and south-west enable hydro power potentials due to the height difference. In general, it can be stated that there are large hydro power potentials where large annual precipitation takes place, as well as where large and water-rich rivers (e.g., Danube, Inn, Enns) are located.

5.2. Austria-Wide Comparisons of the Exergy Amounts

In this section, the three exergy amounts (current exergy consumption, current useful exergy demand as well as the technical exergy potential of RES) are compared Austria-wide. A visual comparison of the three exergy amounts is shown in Figure 10. It shows that the current exergy consumption is higher than the technical potentials of RES. Thus, based on its current exergy consumption, Austria cannot supply itself with renewable energy. However, self-sufficiency can be achieved by a significant reduction in the current exergy consumption towards the current useful exergy demand. This could be achieved by increasing the overall exergy efficiency. In Sections 5.2.1–5.2.3, more detailed comparisons between the different exergy amounts are presented.

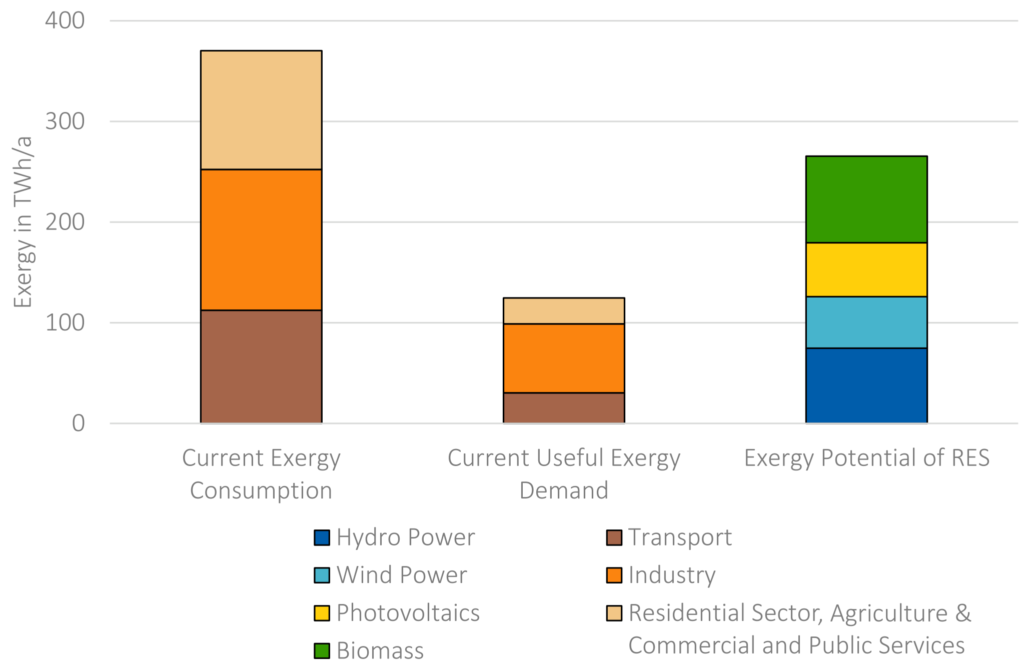

Figure 10. Austria-wide comparison of the current exergy consumption (approx. 370 TWh/a), the useful exergy demand (approx. 125 TWh/a) and the technical exergy potential of RES (approx. 266 TWh/a). In Austria, the current exergy consumption cannot be covered by the technical exergy potential of RES. Therefore, the exergy consumption must be significantly reduced to enable exergetic self-sufficiency. The comparison of the current exergy consumption with the current useful exergy demand shows that significant savings are possible.

5.2.1. Current Exergy Consumption and Current Useful Exergy Demand

The comparison of the current exergy consumption with the current useful exergy demand shows the total exergy efficiency of the overall energy system in Austria: 370 TWh/a of exergy is consumed in order to cover 125 TWh/a of actually useful exergy demand (Figure 10). The difference between these two exergy amounts is the exergetic loss of the whole system. This total loss includes conversion losses, transport losses as well as losses in the final energy application. Austria has a total exergetic loss of 245 TWh/a and, therefore, an overall exergetic efficiency of 34%.

Among all sectors, the industrial sector has the highest current exergy consumption, followed by the transport and the residential sectors. The exergetic efficiency is 49% (industrial sector), 27% (transport sector), 26% (commercial and public services), 20% (residential sector) and 14% (agriculture), respectively (Table 10).

Table 10. Austria-wide comparison of the current exergy consumption and the current useful exergy demand per sector, including the exergetic efficiency. The efficiency is the highest in the industrial sector, since it needs a lot of heat at high temperature levels.

Sector	Current Exergy Consumption in TWh/a	Current Useful Exergy Demand in TWh/a	Exergy Efficiency in %
Industry	140	68	49
Transport	112	31	27
Residential sector	75	15	20
Commercial and public services	36	9	26
Agriculture	7	1	14

In addition, an even more detailed, subsector-resolved comparison is presented in Figures 11 and 12. The ratio between current exergy consumption and current useful exergy demand can be used to determine the efficiency per subsector. The exergetic loss per subsector is the difference between these two parameters.

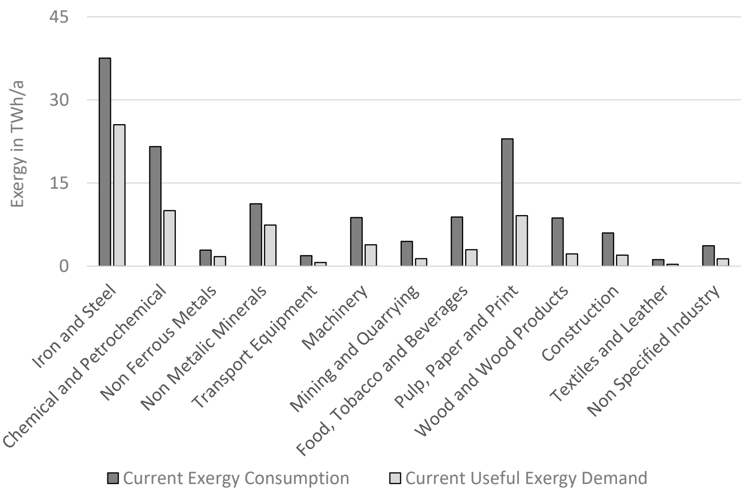

Figure 11. Comparison of the current exergy consumption and current useful exergy demand for different industrial subsectors. The exergetic efficiency for each industrial subsector can be determined by the ratio of these two parameters.

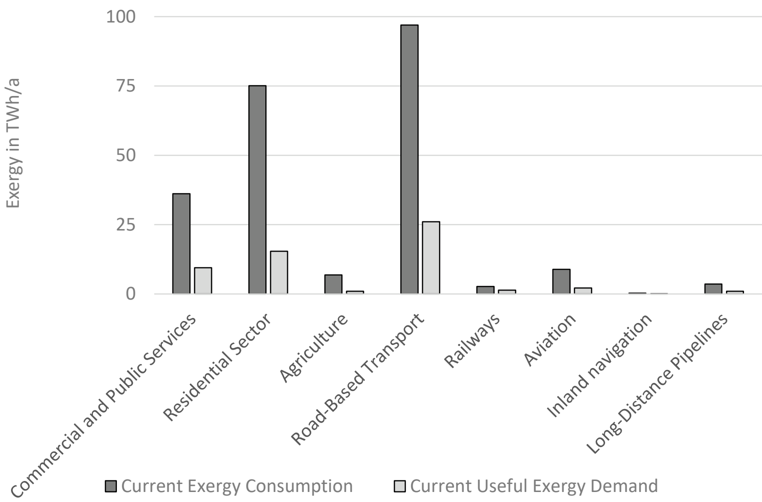

Figure 12. Comparison of the current exergy consumption and current useful exergy demand for commercial and public services, residential sector, agriculture, and different transport subsectors. The exergetic efficiency for each subsector can be determined by the ratio of these two parameters.

The exergetic losses per subsector are shown in Figures 11 and 12. The greatest losses occur in road-based transport (71 TWh/a), followed by the residential sector (60 TWh/a), commercial and public services (27 TWh/a), pulp, paper and print (14 TWh/a), and iron and steel (12 TWh/a).

Since the energy supply in all sectors is almost exclusively based on highly exergetic energy carriers, the large differences in efficiency between the different sectors (industrial, residential sector, commercial and public services, agriculture) can be explained by the different temperature levels of the heat demand. The industrial sector has a high share of the process heat demand on high temperature levels, while the residential sector, commercial and public services, as well as agriculture, need mainly heat on a low temperature level (e.g., for space heating and hot water (Table A2)). Thus, the exergetic efficiency is much lower.

The exergetic efficiency of the transport sector is limited due to the predominance of internal combustion engines and their characteristics. Figures 11 and 12 show that exergy is currently used incorrectly, especially in the field of transport and low-temperature applications such as space heating.

5.2.2. Current Exergy Consumption and Technical Exergy Potentials of RES

The Austria-wide comparison shows that the current exergy consumption is higher than the technical exergy potential of RES (Figure 10). In order to enable renewable self-sufficiency, the exergy consumption would have to be reduced by at least 105 TWh/a, which is 28% of the current exergy consumption. Alternatively, for a completely renewable supply for Austria, renewable exergy imports (e.g., electricity or hydrogen) are necessary.

However, the reduction in the current exergy consumption by 105 TWh/a and a complete expansion of all technical potentials of RES would almost certainly not be enough, since large shares of volatile energy sources are considered in the technical exergy potential (e.g., photovoltaics or wind power). These volatile energy sources require a corresponding infrastructure, which must ensure uninterrupted energy and exergy supply, regardless of the weather or the season. Conversion, storage or transport losses caused by the required infrastructure will have higher losses in the future due to the change in operating mode. A consideration of the infrastructure necessary in the future is explicitly not part of this paper. It will be addressed in further research.

5.2.3. Current Useful Exergy Demand and Technical Exergy Potentials of RES

The current useful exergy demand is much smaller than the exergy potentials of RES in Austria (Figure 10). Thus, if all energy services needed were provided in a way that is exergy optimal, Austria could easily supply itself with renewable exergy. In this exergy optimal case, only about 47% of the total exergy potentials have to be utilized. However, it does not take any exergy losses of the energy supply (mentioned in the previous section) and of the used technology, which provides useful energy, into account. If these losses are also considered, more than 47% of the technical exergy potentials have to be utilized. The difference between the current useful exergy demand and the technical exergy potential of the renewables (141 TWh/a) can be used to cover the losses mentioned. However, the determination of the best technology for final energy applications is explicitly not part of this paper and will be addressed in further research.

5.3. Spatially Resolved Comparison of the Exergy Amounts

5.3.1. Current Exergy Consumption and Current Useful Exergy Demand

The spatially resolved comparison between the current exergy consumption and the current useful exergy demand shows the relative potential for exergy savings per district (Figure 13). It is calculated for each district by subtracting current useful exergy consumption from current exergy consumption, divided by the area of the district. The gray scale ranges from light gray (minimum potential for savings) to dark gray (maximum potential for savings). Please take note of the different scales of all maps. A spatial overview of all provinces and districts in Austria can be found in Appendix B (Figure A1).

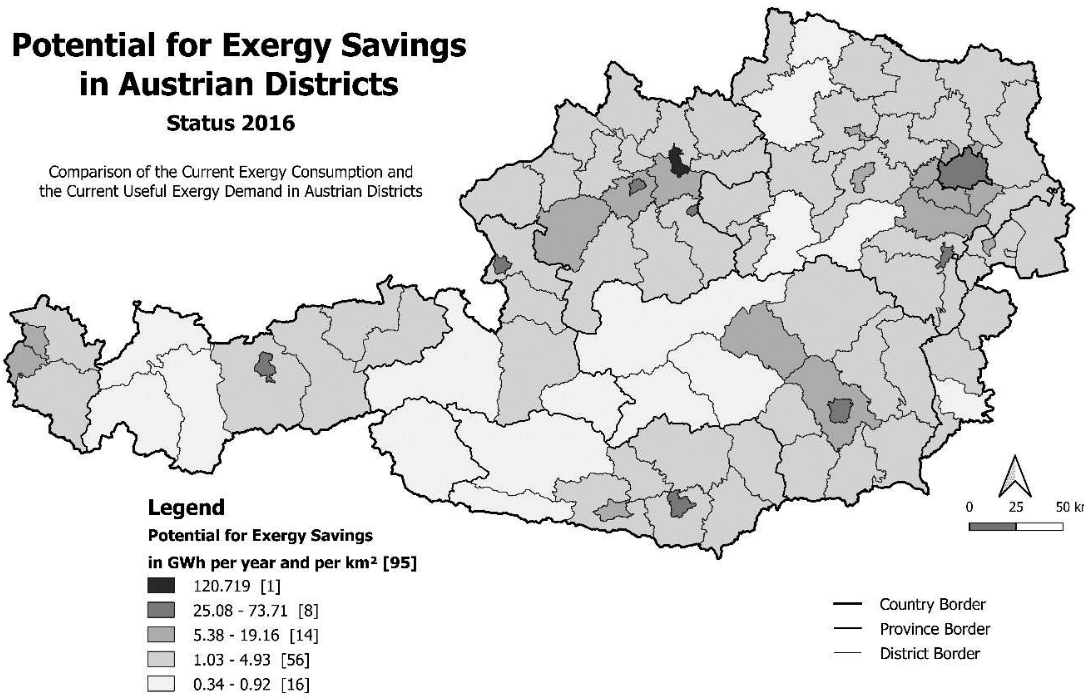

Figure 13. The potential for exergy savings per district can be calculated by the current exergy consumption and the current useful exergy demand. One can see that the districts with a high current exergy consumption (Figure 7) also have a high potential for exergy savings (map source: Statistics Austria - data.statistik.gv.at).

Figure 13 shows that the greatest relative potential for exergy savings can be found in the city of Linz. However, all other urban areas, such as the major cities and their surrounding areas (e.g., Vienna, Graz, Innsbruck or Klagenfurt), as well as some industrial areas, also have large relative potential for exergy savings.

The distribution of the spatially resolved potential for exergy savings can be explained by a direct comparison with the spatially resolved current exergy consumption (Figure 7). Therefore, areas with a currently high exergy consumption also show the greatest potential for exergy savings. The statistical analysis between the current exergy consumption and the current useful exergy demand shows that in Austria, the exergy efficiency per district is rather homogeneous (mean value 31%, standard deviation 7%).

In a district-resolved comparison of the current exergy consumption (Figure 6) with the current useful exergy demand (Figure 7), the share of industry is generally greater for current useful exergy demand than for current exergy consumption. This is mainly caused by the high processing temperatures of the industrial heat demand in contrast to the low temperatures for space heating and hot water.

5.3.2. Current Exergy Consumption and Technical Exergy Potentials of RES

The spatially resolved comparison of the two exergy amounts—current exergy consumption and technical exergy potentials of RES—is shown in Figure 14. The map shows the difference between the current exergy consumption and the technical exergy potentials of RES.

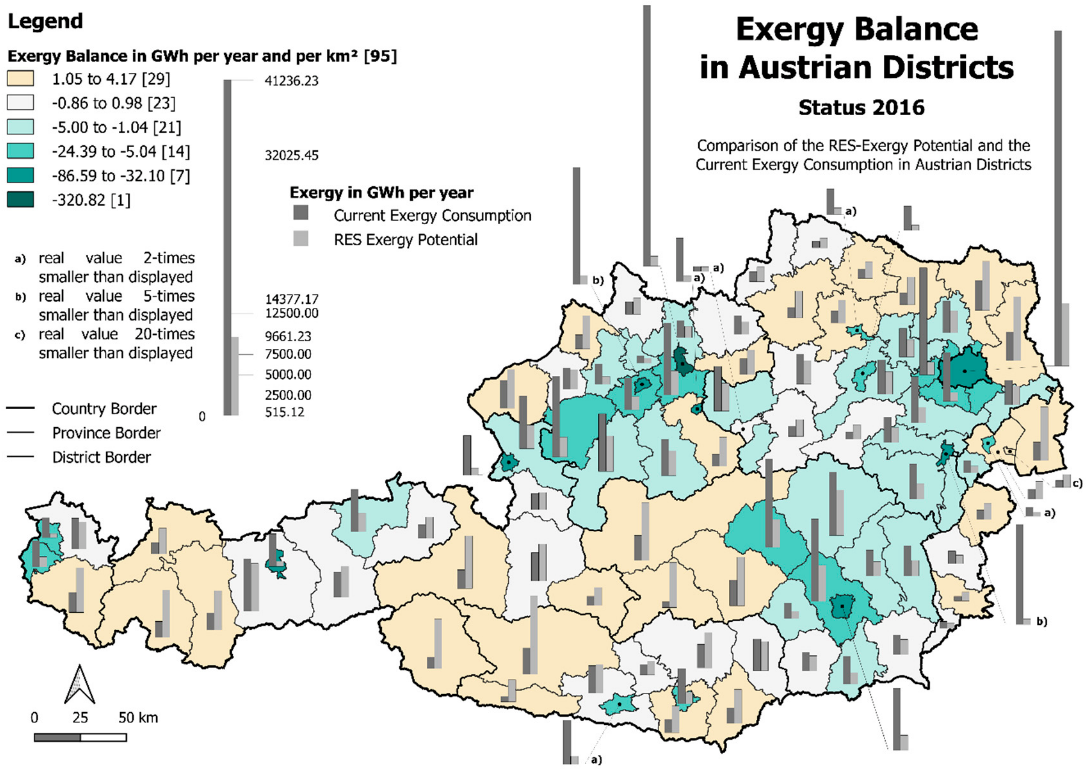

Figure 14. Exergy balance in Austria per district calculated by the technical exergy potential of RES minus the current exergy consumption. One can see that urban and industrial regions have a higher exergy consumption than renewable potential, while the other regions are nearly balanced or have more potential than consumption (map source: Statistics Austria—data.statistik.gv.at).

In this map, there is a bar chart for each district. These bar charts show the absolute consumption (dark gray) and the absolute potential (medium gray) per district. The balance, which is the difference between these two bars, indicates if a district can exergetically supply itself or not. The relative balance, which is the balance divided by the area of the district, is visualized in the background by the shades of color from ocher to blue-green. In ocher colored districts, the potential is higher than the usage or demand, while blue-green colored districts indicate where the potential is smaller than the consumption. Light gray colored districts are almost balanced. Please take note of the different scales of all maps. A spatial overview of all provinces and districts in Austria can be found in Appendix B (Figure A1).

This spatial comparison shows that nearly all districts, with high relative exergy consumption (Figure 7) also have a negative exergy balance (Figure 14). Especially urban areas have a negative relative exergy balance. The area with the worst relative exergy balance is Linz (approx. −321 GWh/(a·km^2)), followed by Steyr (approx. −87 GWh/(a·km^2)) and Vienna (approx. −81 GWh/(a·km^2)). On the other hand, 52 of 95 districts in Austria have a positive relative balance or are approximately balanced.

The reason why this map is comparable to current exergy consumption is that the exergy potential is rather evenly distributed in Austria (standard deviation: 3 GWh/(a·km^2)), while current exergy consumption has a wide variation (standard deviation: 38 GWh/(a·km^2)). Therefore, the difference in the exergy potential cannot significantly change the distribution of the current exergy consumption.

Based on these findings, large energy and exergy flows from the whole of Austria to urban and industrial regions will be necessary in the future. What the infrastructure necessary in the future should look like cannot yet be estimated based on this map, since this paper does not consider the time perspective.

5.3.3. Current Useful Exergy Demand and Technical Exergy Potentials of RES

The last spatially resolved comparison of two exergy amounts is shown in Figure 15. This comparison includes the current useful exergy demand as well as the technical exergy potential of RES. The concept of this map is equivalent to the description in Section 5.3.2. Accordingly, we now refer to the explanation of the map in the previous section.

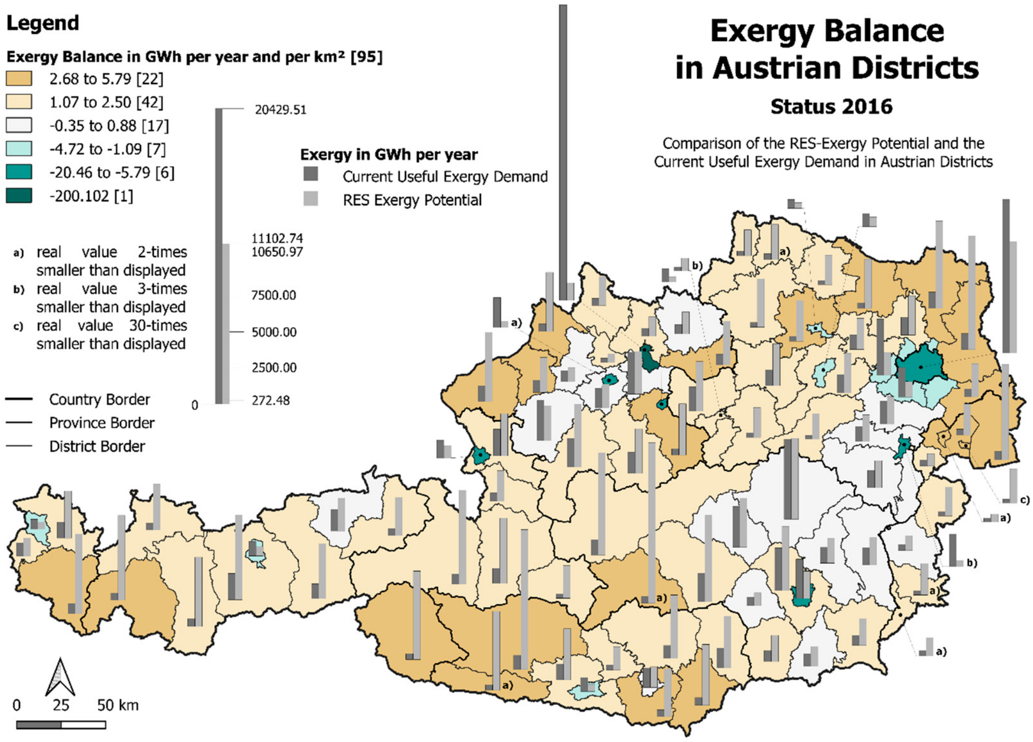

Figure 15. Exergy balance in Austria per district calculated by the exergy potential of RES minus the current useful exergy demand. One can see that in this comparison nearly all districts of Austria have a positive balance or are nearly balanced (map source: Statistics Austria—data.statistik.gv.at).

The spatially resolved relative balance between the current useful exergy demand and the technical exergy potentials of RES is very different, from the balance in the previous Section (Figure 14). In this comparison, almost all districts of Austria have a greater potential than demand, or are almost balanced. Only a few urban areas still have a negative balance (e.g., Linz: −200 GWh/(a·km^2), Steyr: −20 GWh/(a·km^2), Wels: −18 GWh/(a·km^2)). Eighty-one of 95 districts of Austria have a positive relative exergy balance or are nearly balanced (e.g., the industrial regions in Styria and Upper Austria).

This significant difference compared to Figure 15, where only 52 of 95 districts have a positive exergy balance, can be explained by the fact that current useful exergy demand is only about 34% of current exergy consumption.

Figure 15 shows that the excess of the oversupplied districts must be used to supply districts with a negative balance. Therefore, in the future, one challenge will be the exergy transport from the generation site to the consumption site, even if the exergy consumption can be reduced to the current useful exergy demand. Such a significant reduction can only be achieved by changing the used processes and/or the energy service demands.

6. Discussion

In the last few years, different studies have shown that Austria cannot supply itself with renewable energy, even if all renewable potentials are used [4,129,166]. The novelty of this work is that the comparison of the potential and the consumption is made on an exergy level. A comparison of different energy forms (e.g., electricity or heat) and energy carriers (e.g., natural gas, coal, hot water) is more reasonable on an exergy level since exergy considers the quality of energy. Exergy can also be used to determine the actual need of any energy service. Therefore, exergy allows for a much better comparison than energy.

Primary energy consumption, in contrast to final energy consumption, also takes into account the losses of industrial conversion (3% of the primary energy consumption), industrial energy sector use (7% of the primary energy consumption), transport losses (2% of the primary energy consumption), as well as the energy supply system itself (6% of the primary energy consumption). Whether or not this 18% of the primary energy consumption must be considered depends on the specific application. As this paper aims to give a comprehensive overview of the situation in Austria, all these losses must be considered. Therefore, we use the primary energy consumption of Austria as a basis for the determination of current exergy consumption.

In principle, the energy that flows into the system and the energy that flows out of the system is first balanced and then exergetically evaluated. On the one hand, the primary energy consumption is balanced, which is the energy that flows into the national energy system. On the other hand, the useful energy, which is actually needed by all energy services in Austria, is also balanced (Figure 5). The characteristic of services is that they provide useful energy by using final energy. Since the service demand is technology independent, it is reasonable to describe it by the actually required work, which is exergy. According to thermodynamics, the actual exergy demand of a service is equal to the theoretical minimum of the final energy demand of any final energy application. This theoretical minimum can only be reached if the final energy application has no losses and the energy is supplied on the application specific optimal exergy level.

In addition, the Austrian technical potentials of RES are also taken into account in this paper. Subsequently, all three of these so-called exergy amounts were compared, firstly on an Austria-wide basis and then spatially resolved (Figure 1).

6.1. Austria-Wide Results

In Austria, the present energy system, which also includes the final energy utilization, has an exergetic efficiency of 34%. In 2005, Gutschi et al. [3] calculated an exergetic efficiency of about 21% for Austria. The increase can be explained on the one hand by different assumptions (e.g., reference temperature, required temperature levels) and on the other hand by different reference years. For comparison, according to [36], the exergy efficiency of other countries is between 15% and 39%. Due to this low efficiency, Austria cannot cover its exergy consumption with its own exergy potentials of RES. Therefore, in the present energy system, exergetic imports (e.g., hydrogen or electricity) are necessary to realize renewable and CO_2-neutral supply of primary energy. To avoid such primary energy imports, the efficiency of the energy system must be significantly increased. Thus, the final energy utilization and its current technologies must be changed. The following sectors have the lowest exergy efficiency of their final energy applications: agriculture (14%), residential sector (20%) and transport (27%).

In this work, two aspects are not considered. On the one hand, the exergy of waste heat could also be added to the exergy potentials. Such cascaded energy and exergy utilizations increase the efficiency of the overall energy system. For example, the high-temperature waste heat could be used to supply a medium temperature process. Then, the waste heat of the medium temperature process might be used to provide heat at a low temperature level such as for space heating.

On the other hand, this paper also does not include a concept regarding how a future energy supply infrastructure and how the future final energy utilization technologies might look like in order to ensure the highest possible exergy efficiency. Such a concept is necessary to determine how much the current useful exergy demand must be increased, in order to calculate the lowest possible exergy demand. However, further research is required to achieve this.

6.2. Spatially Resolved Results

A spatially resolved holistic view of the Austrian energy system has only been published in the recent work of Abart-Heriszt et al. [5]. The spatially resolved energy consumption in their work was based on very similar approaches and data sources as this work. Probably the most important distinction is that the work of Abart-Heriszt et al. was based on the final energy consumption, while this work is based on the primary energy consumption.

Abart-Heriszt et al. [5] analyzed the different types of land use for the municipalities' energy consumptions and greenhouse gas emissions. Furthermore, they calculated spatially resolved greenhouse gas emissions. In addition to that, in this work, we calculated and compared spatially resolved current exergy consumption and the current useful exergy demand, as well as the technical exergy potential of RES.

The spatially resolved analysis showed that the renewable potential is rather evenly distributed across Austria (standard deviation: 3 GWh/(a·km^2)), although the share of the different renewable potentials varies significantly. In contrast to that, the exergy consumption is mainly located in industrial regions and urban areas (standard deviation: 38 GWh/(a·km^2)). Rural regions show significantly lower exergy consumption. Therefore, in the future, exergy flows from rural regions to industrial and urban areas will be necessary.

6.3. Exergy Potentials of RES

In this study, the spatially resolved technical exergy potential of RES in Austria was calculated. Compared to other Austria-related potential studies, this is the only one based on exergy. Therefore, only selected energy carriers are considered: photovoltaics, wind power, hydro power, and biomass. Solar thermal energy is not taken into account since an exergetic analysis showed that the exergy potential of photovoltaics and the exergy potential of solar thermal energy per area is comparable. The Austrian geothermal potential and ambient heat are also excluded, since the geothermal potential is very limited, and the exergy content of ambient heat is zero per definition. According to IEA guidelines, energy carriers which are difficult to utilize (e.g., sewage sludge) are only taken into account after the conversion to secondary energy carriers (e.g., biogas or biofuels).

A comparison of the already used (reference year 2017, data source: [2]) and currently unused exergy potential of RES in Austria is shown in Figure 16. In this figure, only those energy carriers are taken into account that were also used to calculate the exergy potential in this study. The excluded energy carriers (geothermal, ambient heat, solar thermal and reaction heat) have an overall energy generation of 5 TWh/a [49], but an exergy content of only 0.5 TWh/a (assumed temperatures: solar thermal energy 75 °C, geothermal energy 150 °C, reaction heat 100 °C, ambient heat and surrounding temperature 10 °C). This figure shows that Austria already uses a huge amount of the total available biomass and hydro power potential, but only a very small share of the photovoltaics and wind power potential. Therefore, the utilization of wind and photovoltaics could be increased by about eight and 42 times, respectively.

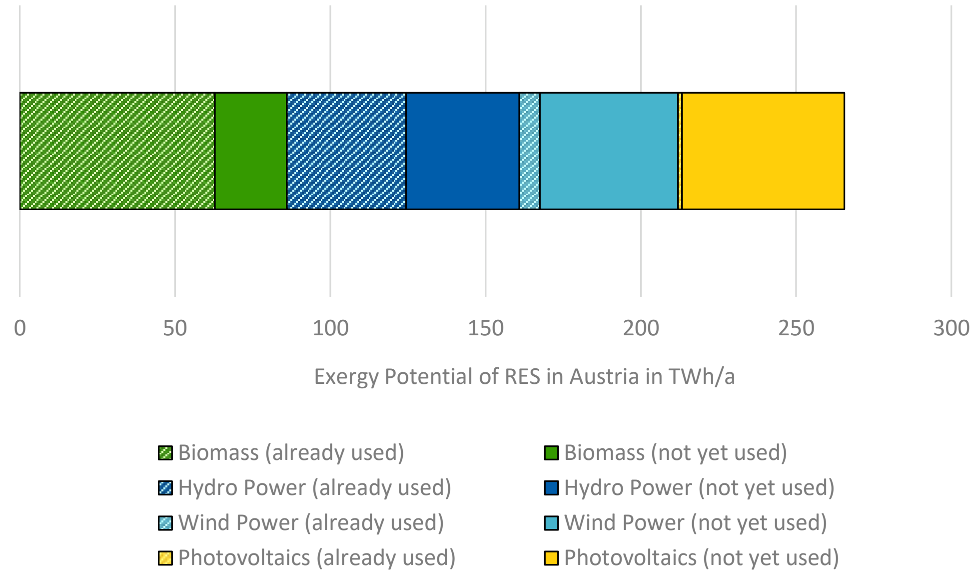

Figure 16. Comparison of the already used and the currently unused potential of RES in Austria. Currently there are only 109 of 266 TWh/a used. One can see that there is a lot of unused potential of wind power and photovoltaics (Source already used renewables in 2017: [2]).

This potential study is difficult compared to other Austria related studies, as it is the only one which is based on exergy, instead of energy. Different types of potential are calculated, assumptions may be different (e.g., competition for area) and different energy carriers are taken into account. Therefore, one cannot directly compare the results of different studies. However, if one neglects energy carriers with no exergy content (e.g., ambient heat) and estimate the exergy content of energy carriers with a low exergy content (e.g., solar thermal systems), it becomes clear that the overall potential of all studies, including this one, are in the same order of magnitude. For comparison, the energy potential of technical potential studies of RES in Austria varies between 266 and 606 TWh/a (Section 3.3.2).

6.4. Uncertainty Analysis

In this section, the uncertainty of the results is discussed. This work is based on different data sources such as statistics, scientific papers or reports. The uncertainty of these data sources is due to their methodology. Where appropriate data are missing, assumptions had to be made. Assumptions that affect energy or exergy only to a small extent do have minor effects on the overall result. The determination of the Austria-wide current exergy consumption and current useful exergy demand is based on only a few assumptions:

- Since the actual share of different light sources in the different sectors in Austria is not published, the share of lighting technologies in the German commercial and public services is used for all sectors in Austria. Lighting causes only about 2% of the primary energy consumption in Austria.
- The sources of the actually used heat temperature statistic (Table A2) do not include the temperature levels of the process heat demand (not space heating) in the sectors agriculture, and commercial and public services. In Austria, the process heat demand of these two sectors is only approx. 2% of the primary energy consumption.
- Where an efficiency or a temperature range is published, we used the mean value of this range. For an Austria-wide analysis, due to the high number of energy and exergy consumers (industrial sides, households, etc.), this mean value should be fairly accurate.
- Self-consumption of power plants, as well as the energy needed for pumping (e.g., for natural gas or district heating), is allocated to the total fossil (except road-based transport, railways, inland navigation and aviation), electrical and district heating energy consumption, since no detailed

data are published. The self-consumption of power plants and consumption for pumping is only 1% of the primary energy consumption.

- The quality factor of chemical energy carriers is assumed as 1 (Section 2.1), since the actual values are difficult to calculate (consideration of all physical and chemical aspects of the surroundings) and no significant deviations occur.
- Due to the usage of a combination of top-down and bottom-up approaches and the usage of various data sources from varying years, there is a difference of about 2% in primary energy consumption between the calculated value and the value published by Statistics Austria (2017).
- Some low exergetic energy carriers (final energy demand of geothermal energy and reaction heat as well as transformation input of solar thermal and geothermal energy) are neglected as they account for less than 0.1% of the total primary energy consumption in 2017.

Based on this uncertainty analysis, current exergy consumption and the current useful exergy demand are reliable (or as reliable as the sources used), since the assumptions cannot significantly change the results.

In contrast, the assumptions that explain the biggest uncertainties are made for determining the spatially resolved results, since a lot of different information is required. For this, not all needed data are published. Due to the lack of available information, there were assumptions necessary to enable spatially resolved results. The main assumptions are:

- Linear correlation of the industrial primary energy consumption and the employees per industrial subsector
- Linear correlation of the primary energy consumption of agriculture and the employees in this sector
- Linear correlation of the primary energy consumption of commercial and public services and the employees in this sector
- Linear correlation of the residential primary energy consumption and the population
- Spatial segmentation of the renewable biomass potential per segmentation factor
- Spatial segmentation of the transport based on the infrastructure.

Whenever possible, the quality of the data was improved by combining different approaches or data sources. For example, for industry, the quality of the spatially resolved results was increased by the combination of a top-down and a bottom-up approach in the industrial sector. The bottom-up approach is based on sustainability reports of industrial companies that enable the direct localization of approximately 40% of the total primary energy consumption, without any uncertainties.

Another example is the determination of the renewable potential. If available, data at the province level are used instead of Austria-wide overall data. Therefore, just spatial separations from provinces to districts were necessary, instead of Austria as a whole to all districts, which increased the quality.

The mixing of different approaches (on one hand the combination of top-down and bottom-up for determining the current industrial exergy consumption and on the other hand an exclusive top-down approach for determining the current industrial useful exergy demand) can cause systemic errors in individual districts and thus discrepancies in direct comparison.

When interpreting the spatially resolved results, it must be considered that there might be some small differences between the calculated result and the actual exergy consumption or demand. Therefore, these spatially resolved values should not be used for the exact detailed planning of some individual small-scale projects (e.g., one separate power line), but they give a good picture of the overall situation in Austria. These results can be used as a basis for further research, such as for spatially resolved energy transition scenarios or optimizations.

7. Conclusions

Many questions are still unresolved when it comes to implementing the energy transition in Austria. To answer these questions, a lot of Austria-related information, such as spatially resolved energy and exergy consumptions, or the technical potentials of RES, are needed. However, since there is no comprehensive data set or spatially resolved exergy-based study of Austria published yet, it is analyzed in this paper.

The main finding of the Austria-wide analysis is that Austria currently has a higher exergy consumption (approx. 370 TWh/a) than all technical exergy potentials of RES (approx. 266 TWh/a). Therefore, even if Austria utilized all its possible renewable exergy potential, it would not be able to be self-sufficient. However, the problem is not caused by the lack of available potential. It is mainly a result of the fact that the current energy system has an exergetic efficiency of only 34%. A significant increase in exergy efficiency would make renewable self-sufficiency in Austria possible. Exergy efficient technologies, cascaded energy utilization and an energy supply infrastructure, which is focused on the actual necessary exergy demand, can help to reduce the overall exergy consumption. Alternatively, if it is not possible to reduce exergy consumption sufficiently, renewable exergy imports (e.g., as electricity or hydrogen) can be used to close the remaining gap.

The main finding of the spatial analysis is the result of the spatial comparison between consumption and renewable potential: The technical exergy potentials of RES in Austria are rather evenly distributed (standard deviation: 3 GWh/(a·km^2)), but the share of the different sources vary. In contrast, the current exergy consumption is mainly focused on urban and industrial areas (standard deviation: 38 GWh/(a·km^2)). Therefore, energy and exergy flows from rural regions to industrial and urban areas will be necessary in the future. Austria will need an energy supply, which can compensate for such spatial differences. In addition, the future energy supply must also be able to balance temporal fluctuations of RES, which is not considered in this study.

Further research can take this study as a starting point. On one hand, as mentioned before, it can be analyzed what the future energy supply infrastructure (e.g., storages, grids) should look like, in order to compensate for the spatial and temporal fluctuations. This could also include a spatially and temporally resolved consideration of the potential of waste heat. On the other hand another subject for research could be which technologies should be used in the future in order to get the current exergy consumption as close as possible to the current useful exergy demand.

Author Contributions: Conceptualization, C.S. and T.K.; methodology, C.S. and T.K.; software, C.S.; validation, C.S., L.K. and F.R.; formal analysis, C.S.; investigation, C.S., L.K. and F.R.; data curation, C.S. and F.R.; writing—original draft preparation, C.S., L.K. and F.R.; writing—review and editing, T.K., and A.T.; maps: L.K.; visualization, C.S., L.K. and F.R; supervision, T.K. and A.T.; project administration, C.S.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

CES	Consumption of Energy Sector Use
CExC	Cumulative Exergy Consumption
CHP	Combined Heat and Power
EEA	Extended Exergy Accounting
Exp	Export
FEC	Final Energy Consumption
FLT	first law of thermodynamics
GIC	Gross Inland Consumption
GIS	Geographical Information System
GSV	Austrian Association for Transport and Infrastructure
ICE	internal combustion engine
ICT	information and communications technology
IDA	Index Decomposition Analysis
IEA	International Energy Agency
Imp	Import
IP	Indigenous Production of Primary Fuels
IPCC	Intergovernmental Panel on Climate Change
LED	light-emitting diode
NEU	Non Energy Use
NGL	Natural Gas Liquids
OECD	Organisation for Economic Co-operation and Development
OSM	Open Street Map
PACS	proportionally allocated consumption of the energy supply
PEC	Primary Energy Consumption
PV	Photovoltaic
RES	Renewable Energy Sources
SLT	second law of thermodynamics
ST	Solar Thermal
SPECO	Specific Exergy Costing
TI	Transformation Input
TL	Transport Losses
TO	Transformation Output
ΔStock	Stock Change

Appendix A

Table A1. This table shows, how the industrial subsector resolved primary energy consumption is calculated, based on energy balances, which are published e.g., by Statistics Austria [2,16]).

Industrial Subsector [1]	Final Energy Consumption	Consumption of Energy Sector Use	Transformation Input	Transformation Output
Iron and steel	Final energy consumption of iron and steel	- Coke ovens - Blast furnaces	- Everything to coke ovens - Everything to blast furnaces - Coke oven gas, and blast furnaces gas to company-owned plants - Natural gas and Hydro power to company-owned plants	- Everything from coke ovens - Everything from blast furnaces - Electricity and district heating from company-owned plants
Chemical and petrochemical	Final energy consumption of chemical and petrochemical	- Oil refineries	- Everything to refineries Hard coal, oil products [2] natural gas, industrial waste, municipal waste (non-renewable), wood waste, biogas and other solid biofuels to company-owned plants	- Everything from refineries - Electricity and district heating from company-owned plants

Table A1. *Cont.*

Industrial Subsector [1]	Final Energy Consumption	Consumption of Energy Sector Use	Transformation Input	Transformation Output
Nonferrous metals	Final energy consumption of nonferrous metals	-	-	-
Nonmetallic minerals	Final energy consumption of nonmetallic minerals	-	-	-
Transport equipment	Final energy consumption of transport equipment	-	- Natural gas to company-owned plants	- Electricity and district heating from company-owned plants
Machinery	Final energy consumption of machinery	-	- Oil products [2] and natural gas to company-owned plants	- Electricity and district heating from company-owned plants
Mining and quarrying	Final energy consumption of mining and quarrying	-	-	-
Food, tobacco and beverages	Final energy consumption of food, tobacco and beverages	-	- Oil products [2], natural gas and biogas to company-owned plants	- Electricity and district heating from company-owned plants
Pulp, paper and print	Final energy consumption of pulp, paper and print	-	- Black liquor, hard coal, oil products [2], natural gas, industrial waste, municipal waste (non-renewable), wood waste, biogas, other solid biofuels, hydro power to company-owned plants	- Electricity and district heating from company-owned plants
Wood and wood products	Final energy consumption of wood and wood products	-	- Natural gas, wood waste, other solid biofuels to company-owned plants	- Electricity and district heating from company-owned plants
Construction	Final energy consumption of construction	-	-	-
Textiles and Leather	Final energy consumption of textiles and Leather	-	-	-
Non specified industry	Final energy consumption of non specified industry	-	- wood for charcoal production	charcoal

[1] Classification by Statistics Austria [2], [2] Oil products are a combination of crude oil and Natural Gas Liquids (NGL), refinery feedstocks, gasoline, kerosene, diesel, gasoil, fuel oil, LPG, refinery gas as well as other oil products.

Table A2. Share of the different temperature levels for heat demand (without space heating) per sector (Source: [113,124,125]. Commercial and public services, as well as agriculture are estimated).

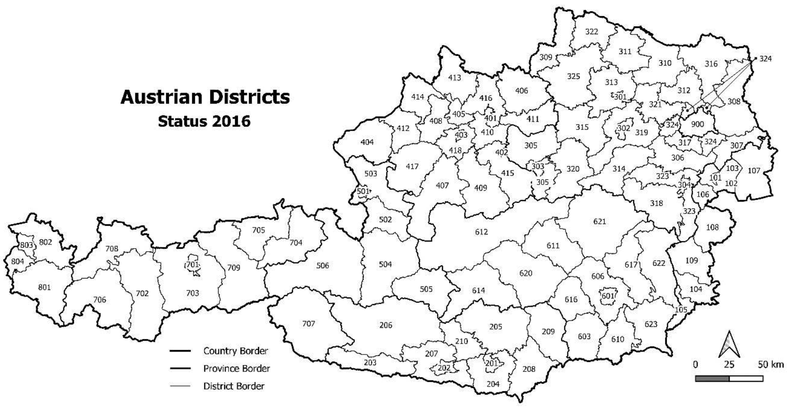
Industrial Subsector [1]	Hot Water	<100 °C	100–200 °C	200–300 °C	300–500 °C	500–1000 °C	>1000 °C
Iron and steel	0.1%	0.6%	0.9%	0.1%	0.7%	19.8%	77.8%
Chemical and petrochemical	0.2%	15.0%	10.5%	6.5%	6.1%	49.5%	12.2%
Nonferrous metals	0.1%	0.6%	0.9%	0.1%	0.7%	19.8%	77.8%
Nonmetalic minerals	0.1%	1.4%	1.2%	0.0%	0.8%	31.4%	65.1%
Transport equipment	10.6%	28.8%	11.5%	0.0%	8.7%	10.6%	29.8%
machinery	10.3%	27.6%	13.0%	0.0%	10.3%	10.8%	28.1%
Mining and quarrying	2.2%	1.4%	0.0%	0.0%	1.9%	30.8%	63.7%
Food, tobacco and beverages	1.1%	44.2%	51.3%	3.4%	0.0%	0.0%	0.0%
Pulp, paper and print	0.6%	18.6%	45.5%	1.9%	33.3%	0.0%	0.0%
Wood and wood products	0.0%	78.9%	10.5%	0.0%	10.5%	0.0%	0.0%
Construction	8.7%	8.4%	0.0%	0.0%	27.7%	17.8%	37.4%
Textiles and Leather	4.0%	96.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Non Specified Industry	2.0%	22.0%	43.0%	2.0%	30.0%	0.0%	2.0%
Commercial and Public Services	0.0%	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%
Residential Sector	84.9%	0.0%	15.1%	0.0%	0.0%	0.0%	0.0%
Agriculture	0.0%	50.0%	50.0%	0.0%	0.0%	0.0%	0.0%

[1] Classification by Statistics Austria [2].

Table A3. Assumed mean temperatures and Carnot Factor for the different heat applications and sources (surrounding temperature 10 °C).

Heat Demand or Source	Assumed Mean Temperature in °C	Carnot Factor in %
Ambient heat	10	0
Space heating	25	5
Hot water	65	16
Solar thermal energy	75	18
District heating	100	24
Process heat <100 °C	100	24
Process heat 100–200 °C	150	33
Process heat 200–300 °C	250	46
Process heat 300–500 °C	400	58
Process heat 500–1000 °C	750	72
Process heat >1000 °C	1500	84

Appendix B



Burgenland

ID	District
101	Eisenstadt(Stadt)
102	Rust(Stadt)
103	Eisenstadt-Umgebung
104	Guessing
105	Jennersdorf
106	Mattersburg
107	Neusiedl am See
108	Oberpullendorf
109	Oberwart

Carinthia

ID	District
201	Klagenfurt Stadt
202	Villach Stadt
203	Hermagor
204	Klagenfurt Land
205	Sankt Veit an der Glan
206	Spittal an der Drau
207	Villach Land
208	Voelkermarkt
209	Wolfsberg
210	Feldkirchen

Vorarlberg

ID	District
801	Bludenz
802	Bregenz
803	Dornbirn
804	Feldkirch

Lower Austria

ID	District
301	Krems an der Donau(Stadt)
302	Sankt Poelten(Stadt)
303	Waidhofen an der Ybbs(Stadt)
304	Wiener Neustadt(Stadt)
305	Amstetten
306	Baden
307	Bruck an der Leitha
308	Gaenserndorf
309	Gmuend
310	Hollabrunn
311	Horn
312	Korneuburg
313	Krems(Land)
314	Lilienfeld
315	Melk
316	Mistelbach
317	Moedling
318	Neunkirchen
319	Sankt Poelten(Land)
320	Scheibbs
321	Tulln
322	Waidhofen an der Thaya
323	Wiener Neustadt(Land)
324	Wien-Umgebung
325	Zwettl

Upper Austria

ID	District
401	Linz(Stadt)
402	Steyr(Stadt)
403	Wels(Stadt)
404	Braunau am Inn
405	Eferding
406	Freistadt
407	Gmunden
408	Grieskirchen
409	Kirchdorf an der Krems
410	Linz-Land
411	Perg
412	Ried im Innkreis
413	Rohrbach
414	Schaerding
415	Steyr-Land
416	Urfahr-Umgebung
417	Voecklabruck
418	Wels-Land

Salzburg

ID	District
501	Salzburg(Stadt)
502	Hallein
503	Salzburg-Umgebung
504	Sankt Johann im Pongau
505	Tamsweg
506	Zell am See

Styria

ID	District
601	Graz(Stadt)
603	Deutschlandsberg
606	Graz-Umgebung
610	Leibnitz
611	Leoben
612	Liezen
614	Murau
616	Voitsberg
617	Weiz
620	Murtal
621	Bruck-Muerzzuschlag
622	Hartberg-Fuerstenfeld
623	Suedoststeiermark

Tyrol

ID	District
701	Innsbruck-Stadt
702	Imst
703	Innsbruck-Land
704	Kitzbuehel
705	Kufstein
706	Landeck
707	Lienz
708	Reutte
709	Schwaz

Vienna

ID	District
900	Wien(Stadt)

Figure A1. Overview of all Austrian districts including the allocation to the provinces (map source: Statistics Austria - data.statistik.gv.at).

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Table A 2. Author statement to the second journal article

Activity	**Contributing authors (the first-mentioned is the main author)**
Conceptualisation	C. Sejkora, T. Kienberger
Methodology	C. Sejkora, T. Kienberger
Data curation	C. Sejkora, L. Kühberger, F. Radner
Software development and validation	C. Sejkora, P. Gradl
Modelling	C. Sejkora
Investigation and analysis	C. Sejkora, L. Kühberger, F. Radner
Visualization	C. Sejkora, L. Kühberger, P. Gradl
Writing (original draft)	C. Sejkora, L. Kühberger
Writing (review and editing)	C. Sejkora, T. Kienberger, F. Radner, A. Trattner

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Exergy as criteria for efficient energy systems – Maximising energy efficiency from resource to energy service, an Austrian case study

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ABSTRACT

The EU aims for complete decarbonisation. Therefore, renewable generation must be massively expanded, and the energy and exergy efficiency of the entire system must be significantly increased. To increase exergy efficiency, a holistic consideration of the energy system is necessary. This work analyses the optimal technology mix to maximise exergy efficiency in a fully decarbonised energy system. An exergy-based optimisation model is presented and analysed. It considers both, the energy supply system and the final energy application. The optimisation is using Austria as a case study with targeted renewable generation capacities of 2030.

The results show, that despite this massive expansion and the maximum exergy efficiency, about half of the primary energy still be imported. Overall exergy efficiency can be raised from today's 34% (Sejkora et al., 2020) to 56%. The major increase in exergy efficiency is achieved in the areas of heat supply (via complete excess heat utilisation and heat pumps) and transport (via electric and fuel cell drives). The investigated exergy optimisation results in an increase of the final electrical energy demand by 44% compared to the current situation. This increase leads to mainly positive residual loads, despite a significant expansion of renewable generation. Negative residual loads are used to provide heat and hydrogen.

1. Introduction

The European Commission's Green Deal [1] aims to make Europe the first climate-neutral continent by 2050. Austria's current government program [2] targets the same aim until 2040. Currently, all technical renewables potentials cannot cover Austria's primary energy consumption (PEC) [3]. This requires a reduction of PEC, which can be achieved: Firstly, by changing behaviour (e.g. shifts in modal split) or by changing/improving passive systems [4] (e.g. thermal insulation, reduction of car weight). Secondly, by increasing the overall energy efficiency of the entire energy conversion chain.

For identifying energy efficiency measures, the entire energy conversion chain from resource to the provision of energy services must be considered [5]. The conversion chain starts with the resources (e.g. coal in the ground) that can be used. After extraction/provision of the resource (e.g. coal mining), it is called primary energy. Primary energy is usually converted into secondary energy to improve usability (e.g. conversion of coal to electricity using power plants). Secondary energy is known as final energy after transport to the final consumer (e.g. via electricity girds). In final energy applications, the final energy is converted into useful energy (e.g. heat or light). This is the last measurable energy flow before meeting the energy service [6]. Finally, useful energy is consumed by the so-called passive system to fulfil an energy service (e.g. thermal comfort or illumination) [4]. Passive systems do not convert energy into any further useable form since they are at the end of the entire energy conversion chain. Technology change of a single conversion unit can cause significant changes since the overall energy efficiency results from the multiplication of all individual energy efficiencies of the whole conversion chain [4]. Therefore, an integrated design of the entire energy system including various energy carriers and multiple sectors (e.g. residential, industry, transport) is crucial [6]. They are also called Multi Energy Systems (MES) [7]. MES models can be helpful to gain the

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required insights [8]. They can address many different perspectives, such as policy-making, development of new business cases, analysis of sector coupling, or entire system planning [9].

There are two different modes of activities to increase the energy efficiency of energy systems [10]: efficiency of supplying energy (considering the conversion chain from resource to final energy) and efficiency of consuming energy (considering the conversion of final energy to useful energy). Studies can be found which address multiple energy carriers and sectors but consider either efficiency of supplying energy (e.g. [11,12]) or efficiency of consuming energy (e.g. [13–15]). Besides this, there are energy efficiency studies available which focus on one single energy carrier (e.g. [16,17]) or one single sector (e.g. [18,19]).

In MES, exergy enables comparability of different forms of energy on a common basis [20]. Exergy is based on the second law of thermodynamics [21] and describes the technical working capacity of a system. However, a system can only perform useful work if it is not in equilibrium with its environment [21]. Depending on the form of energy, a distinction must be made between different concepts of exergy. Exergy associated with heat transfer is calculated via the Carnot factor [22]. Relevant here is the temperature of the system as well as of the environment. Exergy associated with mechanical/electrical energy transfers is equal to the energy transferred [23]. Chemical exergy of a substance refers to the complete (reversible) reaction with the surrounding substances [3]. In contrast to energy, exergy is not conserved. In general, the difference between exergy input and exergy output of a conversion consists of two components [21]: exergy loss (unused exergy in waste flows) and exergy destruction (reduction in workability caused by internal irreversibilities). Several national studies analyse the current exergetic status of the respective country/region (e.g. Austria: [24], Germany: [25], island Samsø in Denmark [26]). Only a few studies address exergy-based optimisation of supplying energy in MES (e.g. [27–29]). Furthermore, exergy analysis of the useful energy demand can be used to calculate the current useful exergy demand (CUED). CUED describes the theoretical minimum exergy requirement to fulfil all current energy services in Austria. It is technology independent and depends solely on the behaviour and needs of society. Austrian CUED has already been published in previous work [3].

All studies we found which focus on both energy efficiency activities and consider multiple energy carriers and multiple sectors are based on cost-optimisation models, without considering exergy (e.g. Germany: [30], Canada: [31], California [32]). These studies present scenario-based transition pathways towards a decarbonised country/state. The results show for instance total cost till decarbonisation, cost-optimal technology-mix or required actions for implementation. All statements are based on assumed costs (e.g. investment, subsidies) and learning curves. However, scenario assumptions are often biased by contemporary discussions and expectations [33]. Therefore, the interpretation of the results requires a comparison of the assumptions with the actual regulatory and market situation. This can be avoided by focusing only on technical aspects such as exergy.

A holistic exergy-based study (including all sectors, all energy carriers, covering the whole conversion chain from resources to energy services) can identify the optimal technology mix to ensure maximum energy and exergy efficiency. In addition, a deeper understanding can be gained by distinguishing between exergy losses and exergy destruction. It should use a greenfield approach to find the optimal future portfolio without any restrictions from the current energy system [9]. The insights gained can be used to determine recommendations for action. These actions can be used for decision-making to increase exergy efficiency (e.g. regulations, subsidies). However, no such study was found. This work will address the following research questions by using the decarbonised Austrian energy system as a case study:

1. Which technologies of final energy applications can maximise Austria's exergy efficiency while covering the required demand?
2. Which technologies of the energy supply system can maximise Austria's exergy efficiency while enabling the required flexibility?
3. What are the interdependencies between technologies of the final energy applications and energy supply system?
4. To what extent can Austria be self-sufficient if the optimal technologies are used and the renewable potentials are expanded according to the 2030 target?

Firstly, the relevant modelling aspects of MES, the system boundaries, the mathematical problem formulation and the analysed case study is presented (section 2). Secondly, the results (section 3) and its discussion (section 4) are shown. The discussion analyses the effects of changing boundary conditions. Finally, section 5 concludes this work. Thereby the key findings to increase exergy efficiency are presented, based on the Austrian case study.

2. Methodology

This section explains the system boundaries and borders (subsection 2.1) as well as the mathematical formulation of the model (subsection 2.2). In addition, the analysed case study is presented (subsection 2.3).

2.1. System boundaries and modelling details

The model used in this work considers all energy and exergy flows within the national borders of Austria. We divide the whole energy system into four blocks (Fig. 1). The first block represents the renewable potentials of Austria which can be utilised, e.g., by photovoltaics. The second block, the energy supply system (ESS), uses the output of the first block to provide the final exergy at the right time, at the right place, in the required form (e.g. electricity, fuel). It must compensate these differences between generation/production and need by using conversion units and storages. In addition, import/export from/to other countries is possible. Import/export is crucial to prevent shortages or handle excesses. In the third block, final energy applications (FEA) convert the final to useful exergy (e.g. heat, shaft work, illumination) to cover society's needs. These needs are described by the CUED (fourth block) and must always be covered.

The system boundaries (Fig. 1) define renewable national generation/production and the CUED (including all sectors[1] and all useful exergy categories[2]). The system boundaries of the ESS allow the usage of a redundant technology pool with multiple conversion chains: The required final exergy can be provided by different conversion units. For any individual time-step, the most exergy efficient conversion route is selected. In contrast, inside the FEA block, a pool of different FEA is available. Over the entire optimisation period, the ratio of the selected technologies (e.g. ratio between fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV)) must be constant. This prevents for example the solver to equip one single car with multiple drives at the same time. The

[1] residential; industry; private and public services; agriculture; transport.

[2] heat demand at wide range of temperatures between 25 and 1500 °C; multiple types of transport demand; electricity demand for ICT (information and communication technology), lighting and electrochemical purposes; work demand of stationary engines; industrial process-related energy demand.

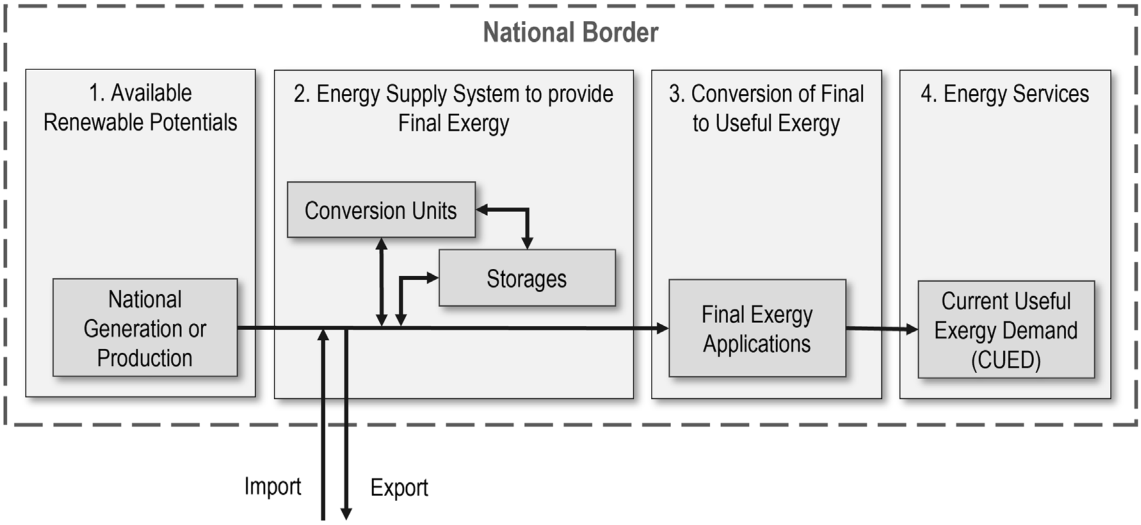

Fig. 1. System boundaries and borders of this work. All exergy flows within the national border and import/export are considered.

used technologies of the ESS (second block) and the FEA (third block), as well as import/export, contribute to the overall exergy efficiency. By considering them, the exergy efficiency of supplying and consuming energy are addressed.

To provide meaningful results, various aspects in MES modelling must be considered [34]: To answer the research questions, a bottom-up approach is used to include technological details. The modelling scope is about the optimal design, using a greenfield approach. For this purpose, operational models are more suitable than planning models. Besides, operational models can address questions about the required flexibility. Therefore, volatility in supply and demand must be considered: Future energy systems will have seasonal, weekly and (sub)daily flexibility needs [35]. Thus, a time-resolved analysis is required and the time horizon is set to one year to include seasonal effects. To ensure maximal energy or exergy efficiency, mathematical optimisation is purposeful. Thereby, a linear programming formulation is chosen, and the assessment criteria is also already defined by the research question: the objective function is about maximising exergy efficiency.

Other relevant aspects in MES modelling [34] will be addressed together. To address the research questions in the maximum depth, a high level of detail is necessary. However, a higher level of detail requires more data, which are not always available [9]. Therefore, the chosen level of detail must consider both the available data and the research questions. In the following, the temporal and spatial resolution, as well as the level of detail about import/export, will be discussed.

Energy systems with a high share of volatile generation have seasonal, weekly and daily flexibility needs [35]. Since the focus of this work is on exergy efficiency, a high temporal resolution is less important: Short-time storages are more energy and exergy efficient than long-time ones. For example, to store electricity, the exergy efficiency of a battery storage cycle is 90% [36] compared to the 42% exergy efficiency [37–40] of a power-to-gas-to-power cycle.[3] Since the losses of thermal storage primarily depend on the storage period, thermal short-time storages are also highly exergy efficient.[4] Chemical energy can be stored efficiently, independent of the storage period. Therefore, with consideration of the available data, a temporal resolution of one day is chosen, which includes seasonal and weekly fluctuations. However, only statements on daily average power can be made. To consider also electric short-time compensation losses (e.g. day/night-balancing), they are assumed as a lump sum.[5]

Spatially resolved models are necessary for analysing energy transmission and distribution [8]. However, such analyses require a power-based consideration with a high temporal resolution. The research questions of this work focus on the optimal technology mix for maximal exergy efficiency. To a first approximation, this is independent of a power-based consideration and energy transmission and distribution. Therefore, an aggregated consideration of Austria is used. It can be interpreted as a system with unlimited internal energy-transportation capacities.

Import or export can be interpreted as shortage or excess, caused by the national generation/production, respectively. Due to the temporal resolution, import/export flows can only be interpreted as the net-balance over one day. Following the 4th research question (self-sufficiency shall be maximised), in this work, exports are only possible, if national generation/production exceeds all demands (period under consideration: one year). We applied system boundaries to limit the maximum capacity of electricity import. By limiting this capacity, we aim to describe the always available and importable foreign volatile generation (i.e. without conversion losses such as photovoltaics).

2.2. Mathematical formulation

In this subsection, firstly, the mathematical formulation of the used MES-model is shown (subsubsection 2.2.1). Afterwards, the objective function is presented (subsubsection 2.2.3).

[3] Considered process: Using water electrolysis to provide hydrogen from electricity, afterwards using a fuel cell for converting hydrogen back to electricity. Excess heat utilisation not included.

[4] As long as the feed-in temperature, the operating temperature of the storage and the feed-out temperature show only slight differences.

[5] The daily storage demand could be determined from the daily component of a discrete Fourier transformation of the difference between electricity consumption and volatile generation [41]. Storage losses can be calculated from the daily storage demand and the energy efficiency ($\eta = 0.9$ [36]). Used data: generation and consumption are used according to case study assumptions. Used load and generation profiles: [42,43].

2.2.1. Exergy MES-Model

To optimise exergy flows in a MES, all energy flow must be evaluated exergetically. An exergy flow Ex_i is calculated by multiplying the corresponding energy flow En_i by its exergy factor $f_{Ex,i}$ (eq. (1)): Electricity has an exergy factor of 1. For chemical energy, the exergy factor is also approximated with 1 [3]. For thermal energies, the exergy factor is determined by the Carnot factor $f_{C,i}$ (eq. (2)) and depends on the temperature of the medium T_i and the temperature of the environment T_0. In this work, the temperature of the environment T_0 is assumed to be 10 °C. This temperature corresponds to the annual mean temperature near the ground in populated areas in Austria [44].

$$Ex_i = En_i \cdot f_{Ex,i} \quad (1)$$

$$f_{C,i} = 1 - \frac{T_0}{T_i} \quad (2)$$

The applied MES-model is implemented by using the Open Energy Modelling Framework (oemof) [45,46]. However, a few adaptions were necessary. In the following, the mathematical formulation of all components of the MES-model is presented:

1. **Buses:** They are required to connect various elements such as sources, sinks, conversion units, storages etc. Buses are lossless. Therefore, the sum of all inputs $Ex_{In,i}$ must be equal to the sum of all outputs $Ex_{Out,k}$ for all time steps t (eq. (3)).

$$\sum_i Ex_{In,i}(t) = \sum_k Ex_{Out,k}\ (t) \quad (3)$$

2. **Sources:** The exergy flow from a source $Ex_{Source,i}$ (e.g. national generation/production, import) must be equal to the accordant exergy input flow of a bus (eq. (4)) for all time steps. If required, time series can be assigned to the source (e.g. renewable generation).

$$Ex_{Source,i}(t) = Ex_{In,\ i}(t) \quad (4)$$

3. **Sinks:** The exergy flow to a sink $Ex_{Sink,i}$ (e.g. exports) must be equal to the exergy output flow of the connected bus for all time steps (eq. (5)).

$$Ex_{Out,k}\ (t) = Ex_{Sink,i}(t) \quad (5)$$

4. **Storages:** The difference in state-of-charge SOC_i between two sequential timesteps of any storage-unit is the exergy charged or discharged ΔEx_i minus exergy storage losses and exergy storage destruction over time $Ex_{LossDest,\ OT,i}$ (eq. (6)). Furthermore, also charging exergy losses and exergy destruction $Ex_{LossDest,Cha,i}$ and discharging exergy losses and exegy destruction $Ex_{LossDest,DisCha,i}$ must be considered (eq. (7)).

$$SOC_i\ (t) - SOC_i(t-1) = \Delta Ex_i(t) - Ex_{LossDest,\ OT,i} \quad (6)$$

$$\Delta Ex_i + Ex_{LossDest,Cha,i} - Ex_{LossDest,\ DisCha,i} = Ex_{in,j} - Ex_{out,j} \quad (7)$$

5. **Conversion units:** They can have multiple-input flows $\vec{Ex}_{CU,In}$ and multiple-output flows $\vec{Ex}_{CU,Out}$ (e.g. gas-fired CHP). The import-output correlation of any multi-port conversion unit can be defined by a matrix multiplication (eq. (8)) [47]. The matrix $\widehat{C}$ consists of constant exergy efficiency factors and maps the input exergy flows to the output exergy flows.

$$\underbrace{\begin{bmatrix} Ex_{CU,Out,i}(t) \\ Ex_{CU,Out,j}(t) \\ \vdots \\ Ex_{CU,Out,z}(t) \end{bmatrix}}_{\vec{Ex}_{CU,Out}} = \underbrace{\begin{bmatrix} C_{i,i} & \cdots & C_{z,i} \\ \vdots & \ddots & \vdots \\ C_{i,z} & \cdots & C_{z,z} \end{bmatrix}}_{\widehat{C}} \underbrace{\begin{bmatrix} Ex_{CU,In,i}(t) \\ Ex_{CU,In,j}(t) \\ \vdots \\ Ex_{CU,In,z}(t) \end{bmatrix}}_{\vec{Ex}_{CU,In}} \quad (8)$$

The indices j to z represent all energy carriers that are connected to the corresponding conversion unit (regardless of whether it is input or output). Element $C_{j,i}$ of matrix $\widehat{C}$ is the exergy conversion efficiency of the exergy of energy carrier i to the exergy of energy carrier j. Accordingly, the exergy conversion efficiency can be calculated from the ratio of exergy input to exergy output (eq. (9)). Following (eq. (1)), the ratio of energy input to energy output including the associated exergy factors can also be used.

$$C_{j,i} = \frac{Ex_{CU,Out,j}}{Ex_{CU,In,i}} = \frac{En_{CU,\ Out,j}}{En_{CU,In,i}} \cdot \frac{f_{Ex,j}}{f_{Ex,i}} \quad (9)$$

As mentioned before, in general, conversion units (eq. (8)) can have multiple inputs and multiple outputs. For this work, only two types of conversion units are relevant: units with single input and one or multiple outputs (e.g. gas-fired CHP or heat exchanger) as well as units with multiple input with only one single output (e.g. heat pump to raise low-temperature excess heat to a higher temperature level).

The $C_{j,i}$ of the first type of conversion units (only one single input) is the energy efficiency $\eta_{En,CU,j}$ of output j multiplied/divided by the exergy factors of input and output (eq. (10)). Accordingly, $C_{j,i}$ can also be seen as the exergy efficiency $\eta_{Ex,CU,j}$ of output j. If a conversion unit of this type has several outputs, there is one individual exergy efficiency for each output. For example, a gas-fired CHP has an exergy efficiency of electricity output in relation to gas consumption as well as an exergy efficiency of thermal output in relation to gas consumption. In this case, the overall exergy efficiency is the sum of all individual exergy efficiencies.

$$C_{j,i} = \frac{Ex_{CU,Out,j}}{Ex_{CU,In,i}} = \frac{En_{CU,\ Out,j}}{En_{CU,In,i}} \cdot \frac{f_{Ex,j}}{f_{Ex,i}} = \eta_{En,CU,j} \cdot \frac{f_{Ex,j}}{f_{Ex,i}} = \eta_{Ex,CU,j} \quad (10)$$

The other type of conversion units (multiple input and single output) can also be calculated according to (eq. (9)). However, this type must not be interpreted according to eq. (10). It is only used to calculate heat pumps for raising low-temperature heat to a higher temperature level.

6. **CUEDs:** They must be covered by the output of FEA, which are conversion units. According to the system boundaries (subsection 2.1), a fixed ratio $r_{i,j}$ between the output of one FEA $Ex_{CU,Out,i,j}$ to the total CUED of one category $Ex_{CUED,j}$ is required (eq. (11)). For example, a constant ratio between BEV related exergy consumption to the total exergy consumption of road transport. The ratio is not predetermined but must be constant for the whole optimisation task (eq. (12)).

$$r_{i,j}(t) = \frac{Ex_{CU,Out,i,j}(t)}{Ex_{CUED,j}(t)} \quad (11)$$

$$r_{i,j}(t) = r_{i,j}(t+1) = const. \quad (12)$$

2.2.2. Exergy losses and exergy destruction

Of any lossy component (such as conversion units, grids, storages), the sum of exergy input $\sum_i Ex_{In,i}$ is equal to the sum of all exergy outputs $\sum_j Ex_{Out,j}$, the sum of all exergy losses $\sum_k Ex_{Loss,k}$ and the exergy destruction Ex_{Dest} (eq. (13)).

$$\sum_i Ex_{In,i} = \sum_j Ex_{Out,j} + \sum_k Ex_{Loss,k} + Ex_{Dest} \quad (13)$$

The relative exergy losses $r_{Ex,Loss,k}$ and the relative exergy destruction $r_{Ex,Dest}$ can be found from the division of (eq. (13)) by the input term $\sum_i Ex_{In,i}$ (eq. (14)). For all conversion units discussed in this paper, the first term can be described by the sum of all $C_{j,i}$ values.

$$1 = \underbrace{\frac{\sum_j Ex_{Out,j}}{\sum_i Ex_{In,i}}}_{\sum_j \sum_i C_{j,i}} + \sum_k \underbrace{\frac{Ex_{Loss,k}}{\sum_i Ex_{In,i}}}_{r_{Ex,Loss,k}} + \underbrace{\frac{Ex_{Dest}}{\sum_i Ex_{In,i}}}_{r_{Ex,Dest}} \quad (14)$$

In general, the relative exergy loss can be calculated by the absolute exergy loss over the sum of all exergy inputs (eq. (14)). This equation is valid for all types of lossy components. For the first type of conversion units (single input, multiple outputs), storages, and grids, the equation can be simplified. To calculate the relative exergy losses $r_{Ex,Loss,k}$, the share of energy loss k (determined via the energy efficiency) is multiplied by the ratio of the exergy factors of input i and loss k (eq. (15)).

$$r_{Ex,Loss,k} = \left(\frac{En_{Loss,k}}{En_{In}}\right) \cdot \frac{f_{Ex,Loss,k}}{f_{Ex,i}} \quad (15)$$

The exergy factor of the loss is calculated for direct thermal losses (e.g. exhaust gas) using the unused excess heat flow's temperature (e.g. exhaust gas temperature). In the case of non-direct thermal losses (e.g. friction), the temperature of the resulting warming due to the loss is used. Lossy components can have several exergy losses at different temperature levels. Finally, the relative exergy destruction $r_{Ex,Dest}$ can be determined after calculating the exergy efficiencies $C_{j,i}$ as well as the exergy losses from (eq. (14)). This calculation of exergy destruction can also be used for conversions with neglected exergy losses (energy efficiency approximated to 100%), such as heat exchangers in the district heating grid.

2.2.3. Objective function

Following the research questions, the total exergy efficiency is to be maximised. Maximum exergy efficiency causes minimal total of exergy losses and exergy destruction. The total of exergy losses and exergy destruction can be determined by the difference between the total CUED $Ex_{CUED,tot}$ and the total exergy used for supply $Ex_{Sup,tot}$. The total exergy used for supply is the sum of all national generations/productions $Ex_{NatGP,i}$ and the difference between all exergy imports $Ex_{Imp,j}$ and exports $Ex_{Exp,k}$ (eq. (16)).

$$\min\ Ex_{LossDest,tot} = Ex_{Sup,tot} - Ex_{CUED,tot} = \sum_i Ex_{NatGP,i} + \left(\sum_j Ex_{Imp,j} - \sum_k Ex_{Exp,k}\right) - Ex_{CUED,tot} \quad (16)$$

All inflows and outflows of each individual component of the MES (buses, conversion units and storages) as well as the outflow of sources and the inflow of sinks are optimisation variables from a mathematical point of view. These optimisation variables are constrained by various boundary conditions. In addition to the boundary conditions (eq. (3)) to (eq. (8)), CUED must always be covered and sources representing renewable production/generation must always be used (subsection 2.1). Accordingly, for the formulation of the objective function, the sum of all national generations/productions as well as the total CUED are neglected since they are defined as constant (via boundary condition). Only the imported/exported exergy is relevant for the national exergy efficiency (eq. (17)). Exergy efficiency can be improved by a reduction of exergy import and increased exergy exports over the national borders.

$$\min f = \sum_j Ex_{Imp,j} - \sum_k Ex_{Exp,k} \quad (17)$$

Consequently, exergy imports and exergy exports are the only optimisation variables that are directly included in the objective function. However, since all components (and accordingly all optimisation variables) are connected by the fundamental mathematical relationships of the MES (subsubsection 2.2.1), all other optimisation variables also influence the objective function indirectly.

2.3. Definition of the case study

In this section, the analysed Austrian case study is presented. According to the current government program [2], Austria intends to expand renewable electricity generation by 27 TWh/y until 2030. Furthermore, it aims to completely decarbonised by 2040. These two goals are the fundaments for the case study used. In this case study, the following energy carriers are considered: electricity, hydrogen, sustainable methane,[6] woody biomass, wood gas, kerosene, ethanol fuel/biodiesel, heat on different temperature levels. In the following, the assumptions of renewable generation, CUED, available technologies and import/export are discussed.

2.3.1. National exergy generation/production[7]

The additional electricity generation capacities according to the current government program are added to the renewable electricity generation in 2018. Renewable generation/production of energy types that are not addressed by the program, the value of 2018 is assumed. Normalised generation/production profiles together with annual exergy generation/production values are used to create supply time series (Table 1). All values in this table represent the annual exergy potential.

[6] In this paper, sustainable methane is methane (CH_4) from renewable sources, regardless of the production process (anaerobic digestion in the biogas plant, gasification of wood and subsequent methanation, methanation of hydrogen, etc.).

[7] In this paper, the provision of primary and secondary exergy from the conversion of natural sources (e.g. sunlight or renewable raw materials) is referred to as "renewable production" or "renewable generation" for simplification purposes. The authors are aware that energy and exergy can never be produced or generated, only converted.

Table 1
Renewable exergy generation/production.

Type	Exergy in TWh/y	Profile
Photovoltaics	12.4[a]	Generation in Austria 2019 [42]
Wind Power Stations	16.0[a]	Generation in Austria 2019 [42]
Hydropower Plants	42.6[a]	Generation in Austria 2019 [42]
Woody Biomass Production	41.9[b]	Assumed as constant
Sustainable Methane Production	2.7[c]	Assumed as constant
Ethanol fuel/Biodiesel Production	2.3[d]	Assumed as constant
Industrial Low-Temperature Excess Heat	1.6[e]	Combined industrial load profile [48]

[a] National electricity generation in 2018 [49] plus expansion according to the current government program [2].
[b] National woody biomass production for energy usage in 2018 [49]. The determination of the exergy is based on an average lower heating value of 3.6 kWh/kg.
[c] National production of landfill gas, sewage gas and biogas [49]. The determination of the exergy is based on an average lower heating value of 13.9 kWh/kg.
[d] National production of biodiesel and bioethanol from national feedstocks in 2017 [50]. The determination of the exergy is based on an average lower heating value of 10.3 kWh/kg.
[e] Energy potential of industrial excess heat in Austria is 21 TWh [51], for exergy assessment, the average temperature is assumed to be 34 °C [52].

Table 2
Current useful exergy demand (CUED).

Type	Exergy in TWh/y	Profile
Transport Demand Car & Trucks	29.5	Car: [53,54]; Trucks: Assumed as a constant with consideration of the weekend driving ban for trucks in Austria [55]
Transport Demand Others	5.0	Austrian Transport Report 2017 [56]; Measured values of Austrian Railways [57]; pipelines assumed as constant
Heat Demand (up to 100 °C)	18.8	FfE SigLinDe [58], A, B
Heat Demand (100–400 °C)	11.6	A, B
Heat Demand (above 400 °C)	15.2	A
Industrial Processes (Iron- and Steelmaking, Electrochemical Demand, Non-Energy Use)	28.7	Iron- and Steelmaking assumed as constant, rest: A
Stationary Engine Demand	16.1	A, B
Lighting and ICT Demand	4.3	A, B

A: Combined industrial load profile [48], no characteristic seasonal changes are assumed to occur [59,60], e.g. caused by weather conditions.
B: Synthetic load profiles [61].

2.3.2. CUED

The CUED for Austria was already published in a previous work [3]. In that work, the CUED was calculated for each sector and useful energy category (footnotes 1 and 2). It is assumed, that CUED used in this study is equal to today's one [3], necessary to cover all current energy services. The only two change compared to the values published in the previous publication is the consideration of energy losses of the heat demand as well as the replacement of the blast furnace route, used for the national crude steel production. Instead, a process based on direct reduction using hydrogen and a subsequent electric arc furnace is considered. This adjustment is crucial to achieve the goal of decarbonisation. The demand and the used profiles of summarised categories are presented in Table 2.

2.3.3. Available technologies

All technologies, storages, and conversion units available for the optimisation task represent the current state of technology with the best available exergy efficiency in each case. Design sizes of all technologies, storages and conversion units (power, capacity) are not limited. All associated exergy efficiencies, exergy losses and exergy destruction as well as all assumptions can be found in the appendix in Tables A 1–A 11. In addition, the direct process demands (e.g. methane as input material in chemical industries) are listed in Table A 12. For these demands, no energy or exergy efficiency is available, as it is a passive system and not an energy conversion system.

2.3.4. Import and export capacities

In this work, only the net-balance of import/export per day is relevant (subsection 2.1). However, the import/export capacity of electricity is limited to 1 GW daily average power. According to the goal of full decarbonisation, the import of electricity must be provided by renewables only. Since it is hard to estimate the amount of volatile generation surplus of neighbour countries in future, we used the current net-import as the basis: In 2018, Austria had an electricity net-import of about 8.9 TWh [49]. Therefore, a daily net-balance capacity limit of 1 GW would result in a total net-balance per year in the range of the net-import of 2018.[8] Import/export capacity of other grid-based energy carriers (sustainable methane, hydrogen) are not limited, since Austria has neutral gas import capacities of about 400 TWh/year [62]. Woody biomass and ethanol fuel/biodiesel have also no import limit since there is no natural limit. The import can be constantly increased by trucks, trains or ships.

3. Results

An optimal design could decrease the Austrian primary exergy consumption from today's 370 TWh/y [3] to 230 TWh/y. This is a reduction of 38% (−140 TWh/y). Thereby, the exergy efficiency in Austria rises from 34% [3] to 56%. Despite the massive expansion of renewables according to the case study and the increased exergy efficiency, 49% (112 TWh/y) of the required primary exergy must be imported. In the following, first the resulting ESS and then the FEA are presented. Finally, the occurring exergy losses and exergy

[8] 1 GW * 8760 h = 8.76 TWh

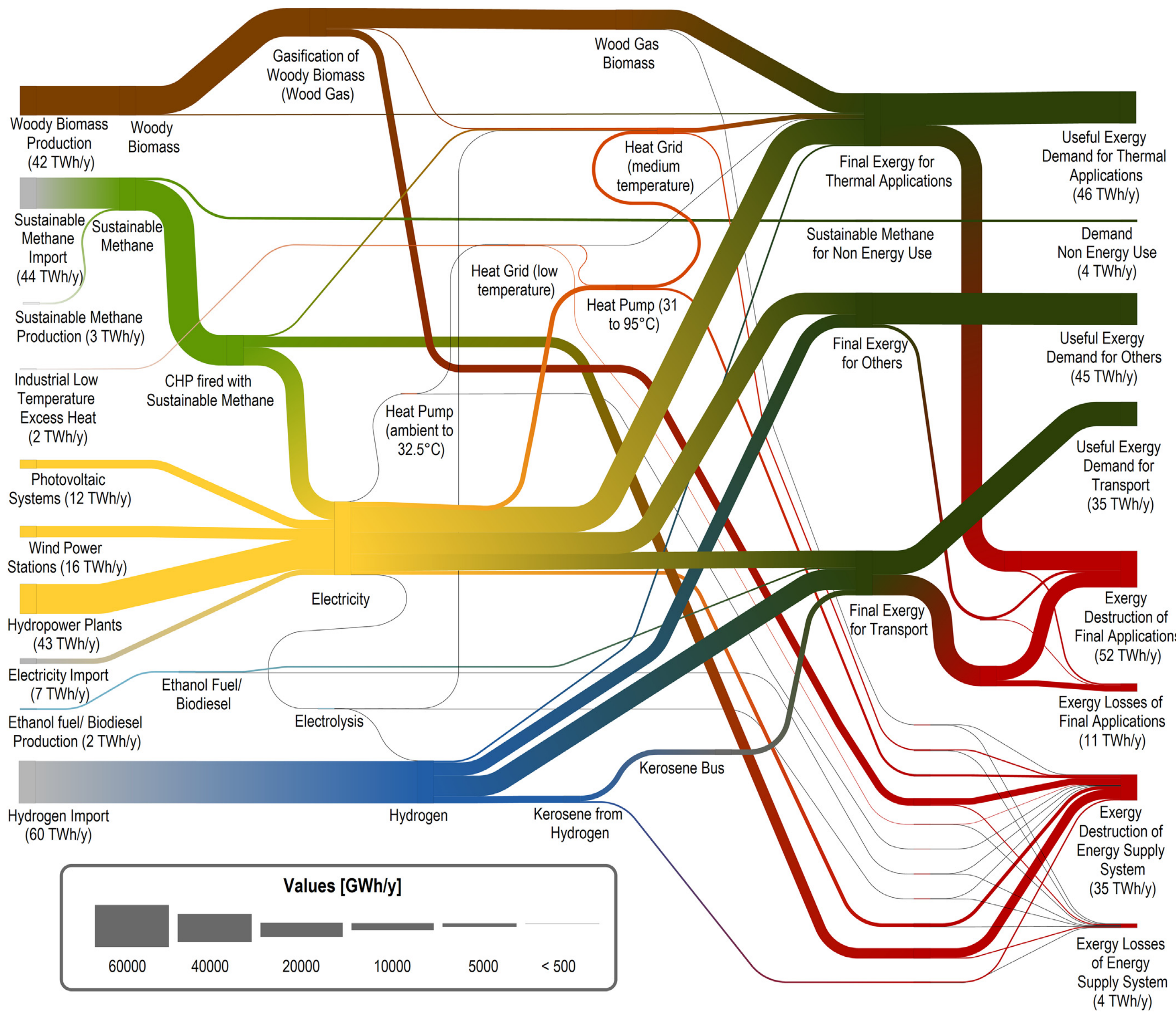

Fig. 2. Grassmann diagram of the energy supply system.

destruction are addressed.

The resulting ESS consists of sustainable methane fired CHPs, electrolysis, gasification of woody biomass, a conversion from hydrogen to kerosene via Fischer-Tropsch synthesis, storages, as well as a low-temperature (feed-in: 34 °C, feed-out: 27.5 °C) and a medium-temperature (feed-in: 92 °C, feed-out: 80 °C) district heating grid (Fig. 2). Both heating grids are mainly supplied by excess heat. It is feed-in, following excess heat's temperature level. Thereby, all available excess heat is used. In addition to excess heat utilisation, there are two heating grid-related heat pumps: one for supplying the low-temperature grid with ambient heat (ambient to 34 °C) and another one for rising the temperature level from low to medium (31–90 °C). Both district heating grids have their individual thermal storage (average temperature at 87.5 and 31.75 °C) to decouple the occurrence of excess heat, the operation of the heat pump and the heat demand. The heating grids as well as all mentioned units of the ESS are centralised. In contrast to the ESS, the FEA are decentralised, which mean, that each consumer (e.g. building) has its own conversion unit (e.g. decentralised grid-bound and non-grid-bound heat pumps) to cover its specific CUED. An overview of the used technologies for FEA is shown in Fig. 3.

Fig. 2 shows the importance of renewable gases (wood gas, hydrogen, sustainable methane) despite the strong utilisation of electricity. Renewable gas accounts for 93% of total imports, electricity only for 7%. However, 43 TWh_{SM}/y of 105 TWh_{H2+SM}/y are used for controllable national electricity generation, mainly in winter (Fig. 4B, Fig. 5). Thereby, sustainable methane fired CHP or fuel cells can be used since the exergy efficiencies are comparable. Import electricity plus volatile and controllable electricity generation results in a total supply of 104 TWh_{el}/y. The exergy optimal design results in a significant increase of the final electrical consumption by 44% compared to 2018 [49]. This increase in consumption causes a mainly positive daily mean residual load[9] (73%

[9] Residual load is defined by finale electricity demand minus volatile electricity generation. It must be compensated by the ESS.

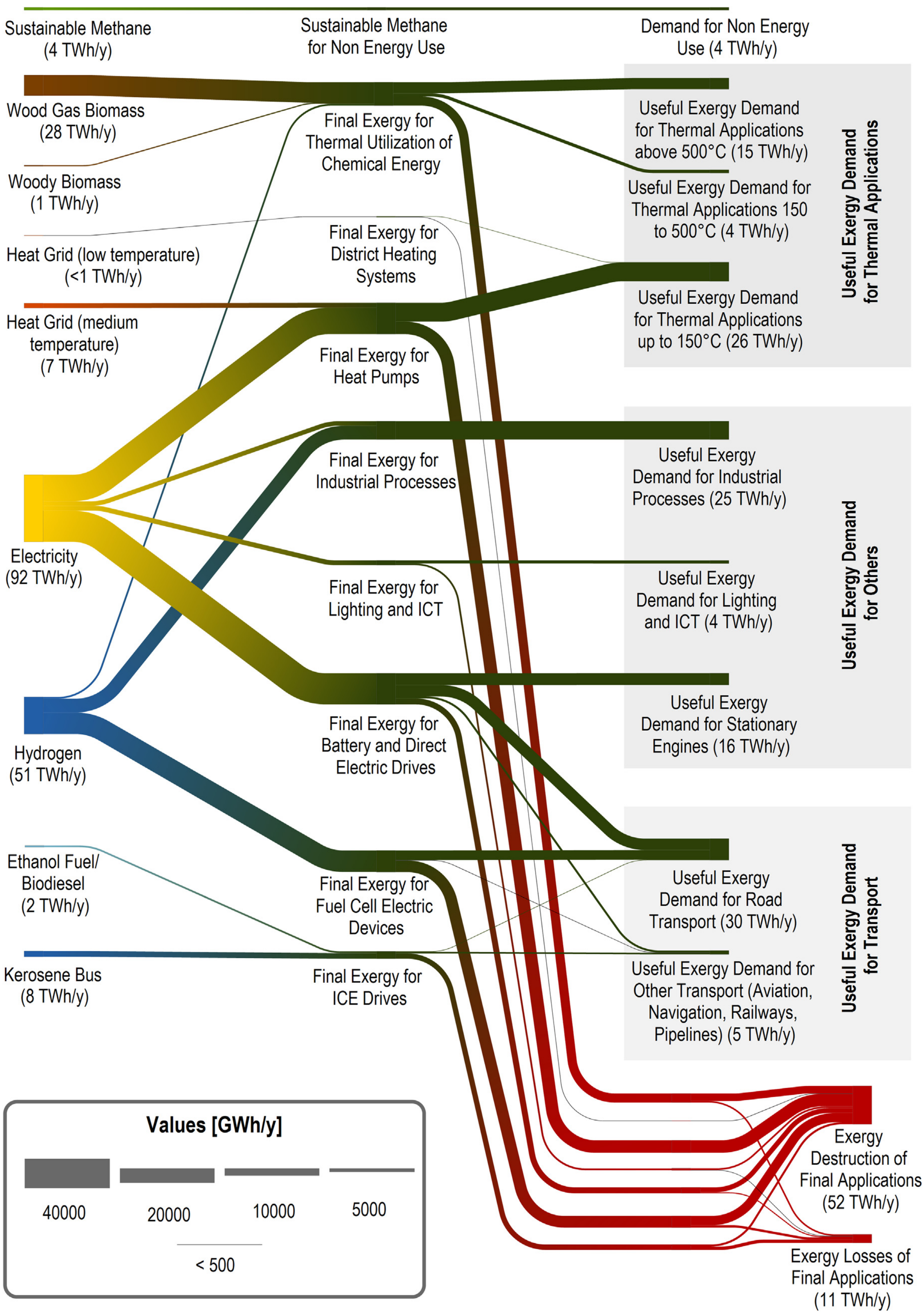

Fig. 3. Grassmann diagram of the final energy application.

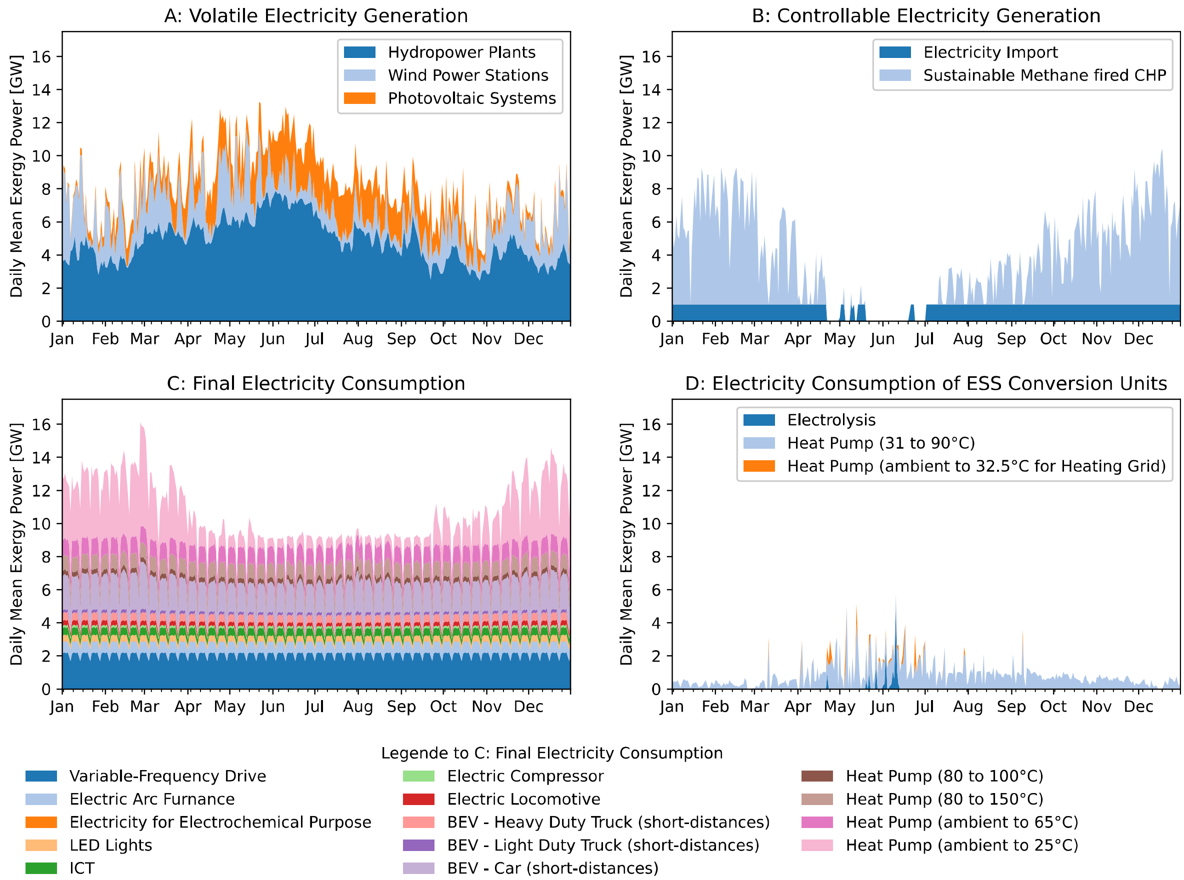

Fig. 4. Electricity supply via volatile (A) and controllable (B) electricity generation as well as electricity usage for final electricity consumption (C) and as input of ESS conversion units (D).

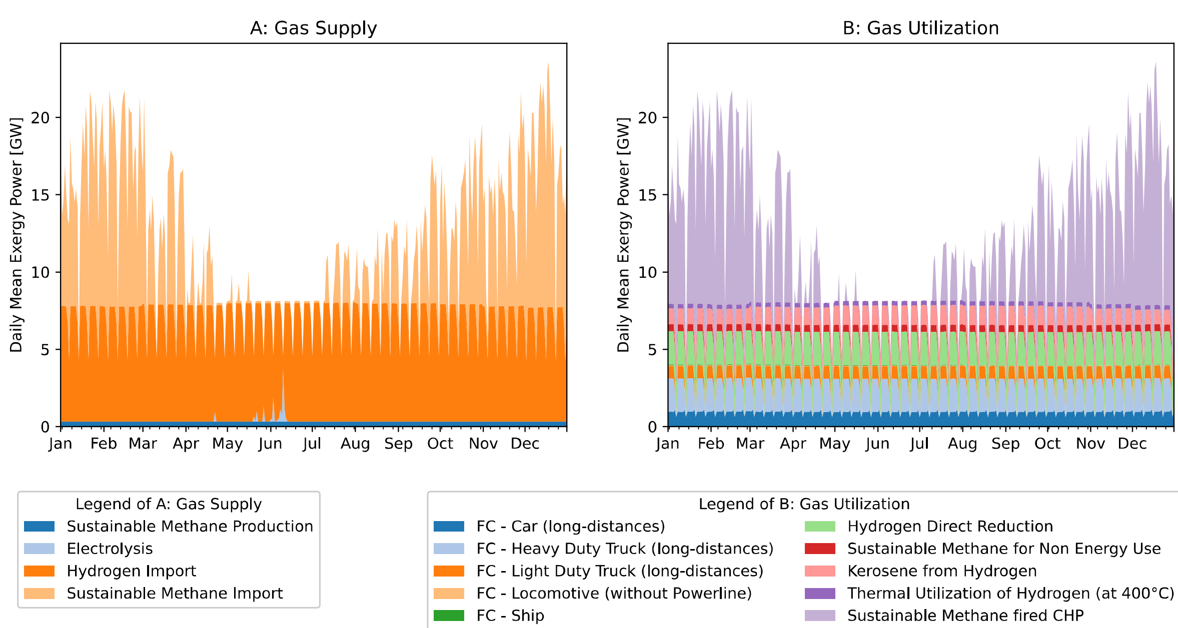

Fig. 5. Total gas supply (A) and utilisation (B).

of all days), despite the significant expansion of volatile electricity generation. The positive residual load takes mainly place in winter since photovoltaic/hydropower generation is highest in summer and the final electricity consumption of decentralised heat pumps for space heating (ambient to 25 °C) is mainly in winter (Fig. 4A–C). About 96% (40 TWh_{WB}/y) of the woody biomass is converted to wood gas. Electricity is used to supply the electrolyses (0.4 TWh_{el}/y), which is used exclusively in the case of electricity surpluses (Fig. 4D). Less than 0.5% of total hydrogen consumption is covered by electrolysis output. Methanation of hydrogen to produce sustainable methane is never used since sustainable methane could be directly imported.

3.1. Covering thermal demand

The FEA for covering the thermal CUED consists of a mix of the incineration of chemical energy, the use of decentralised heat pumps, as well as the use of district heating (Fig. 4). In the following, first the thermal FEA and afterwards their interaction with the district heating grids, are discussed.

In winter, all available low-temperature excess heat is used to cover space heating demands. The rest (97%) and the demand for process heat at 65 °C are covered by decentralised heat pumps (HP ambient to 25 °C: 17.8 TWh_{el}/y; HP ambient to 65 °C: 8.9 TWh_{el}/y). Medium-temperature district heating is used as input for two decentralised heat pumps to cover the process heat demand at 100 °C and at 150 °C (HP 80–100 °C: 2.3 TWh_{el}/y; HP 80–150 °C: 7.2 TWh_{el}/y). Since the COP of heat pumps depends on the temperature spread, high temperatures can only efficiently be suppled by lifting excess heat. Chemical energy is used to cover heat demand at higher temperature levels. Woody biomass can be used up to 250 °C (in total: 1.5 TWh_{WB}/y), higher temperatures require the incineration of gases[10] (wood gas: 28.1 TWh_{WG}/y between 400 and 1500 °C, hydrogen: 2.4 TWh_{H2}/y at 400 °C). In terms of energy and exergy efficiency, renewable gases for incineration are interchangeable. Direct electric heat is never used to cover any thermal demand.

The low-temperature heating grid is mainly supplied by the industrial excess heat (91%, 1.6 TWh_{th}/y). Rest is provided via the centralised heating grid supplying heat pumps (0.2 TWh_{th}/y). About 24% (0.3 TWh_{th}/y) is directly used for the low-temperature space heating system while 1.0 TWh_{th}/y are used to supply the medium-temperature heating gird via the centralised heat pump (output at 90 °C: 4.7 TWh_{th}/y). In addition, the medium-temperature grid is also supplied by the excess heat of woody biomass gasification (1.4 TWh_{th}/y) and sustainable methane fired CHPs (2.4 TWh_{th}/y). Excess heat from electrolysis is neglectable. The exergy in the medium-temperature gird is entirely used for process heat supply (at 100 °C and 150 °C via decentralised heat pumps).

Space heating is the only thermal demand which has a seasonal change (Fig. 4C). All other demands as well as the industrial excess heat are nearly constant over the year. In winter, industrial excess heat is fully used for covering low-temperature space heating demand via the low-temperature heating grid (Fig. 6A+C). In summer, when the space heating demand is low, it is first lifted to the medium-temperature grid then further lifted to provide process heat at 100 °C and 150 °C. In winter, this process heat demand (at 100 °C and 150 °C) is covered by excess heat of the CHPs and of the gasification (Fig. 6B+D). This operation ensures an exergy-efficient supply. Medium-temperature storage (about 64 GWh capacity) is only used as a buffer: it allows flexible operation of the centralised district heating grid's heat pump (31–90 °C) to utilise electricity surpluses if possible (Fig. 4D). The thereby required heat at 31 °C is provided by the low-temperature grid and storage. In contrast, the low-temperature storage (about 25 GWh capacity) is used for both, as a short time buffer and to store heat over longer periods such as weeks and months (Fig. 6).

3.2. Covering transport demand

Transport is mainly based on electric drive systems (electric locomotives: 2.0 TWh_{el}/y; BEV: 21.1 TWh_{el}/y) and fuel cell drives (fuel cell locomotives: 0.3 TWh_{H2}/y; FCEV: 28.9 TWh_{H2}/y; fuel cell ships: 0.2 TWh_{H2}/y) for land transport and navigation as well as internal combustion engines (ICE) for aviation (Fig. 3). Fuel cell drives are used, if a battery system is not feasible due to the required range and overhead wiring is not available. In addition, the available national production of bioethanol fuel/biodiesel (according to the case study) is utilised in ICE for land transport (2.3 TWh_{BD}/y) since there is no other utilisation possible available. However, no additional bioethanol fuel or biodiesel for land transport is imported or produced from hydrogen or sustainable methane since ICEs has a significantly lower energy and exergy efficiency than BEVs or FCEVs (including energy supply). Nevertheless, aviation is supplied with kerosene, produced via Fischer-Tropsch-Synthesis from hydrogen, due to a lack of alternative technologies and no possibility of kerosene imports (10.0 TWh_{H2}/y). Exergy optimal technologies can increase exergy efficiency significantly. For example, the exergy efficiency of road transport increased from 27% in 2018 [3] to 56%.

About 14% of the total energy demand of BEVs are used for passenger comfort (heating and cooling). Heating requires about 80% of the total energy for passenger comfort. Therefore, the electricity demand of BEVs is slightly higher in winter than in summer (Fig. 4C). In contrast, passenger comfort in FCEV (only cooling) requires only 1% of the total energy demand since the excess heat of the drive can be used for heating.

3.3. Covering other demand

To maximise exergy efficiency, all stationary engines and pipeline compressors are electric drives equipped with variable frequency control (stationary engines: 18.3 TWh_{el}/y, compressors: 1.2 TWh_{el}/y). In addition, electricity electric arc furnaces (6.0 TWh_{el}/y), ICT (3.9 TWh_{el}/y), lighting (2.8 TWh_{el}/y) and industrial electrochemical processes[11] (0.2 TWh_{el}/y) are used (Fig. 3). The process-related demand of gases is about 22.6 TWh_{H2+SM}/y (including demand for non-energy use). They are mainly used for direct reduction in iron- and steelmaking (84%). None of these mainly industrial consumers show seasonal changes in demand (Figs. 4C and 5B).

3.4. Exergy losses and exergy destruction

In this work, the total exergy losses of the entire energy system amount to 15.1 TWh/y (7% of the primary energy input) while the total exergy destruction amount to 87.3 TWh/y (38% of primary energy input, Fig. 2). The exergy losses and exergy destruction are classified into two types: exergy losses and destruction of the ESS (38%) and exergy losses and exergy destruction of FEA (62%).

The largest exergy destruction in ESS occurs in sustainable methane fired CHPs (13.4 TWh/y), gasification of woody biomass

[10] It is assumed that the combustion of biomass can only be used for indirect heat supply (e.g. via steam) due to the usual construction forms (e.g. grade firing).

[11] Without electrolysis since it is considered as conversion unit.

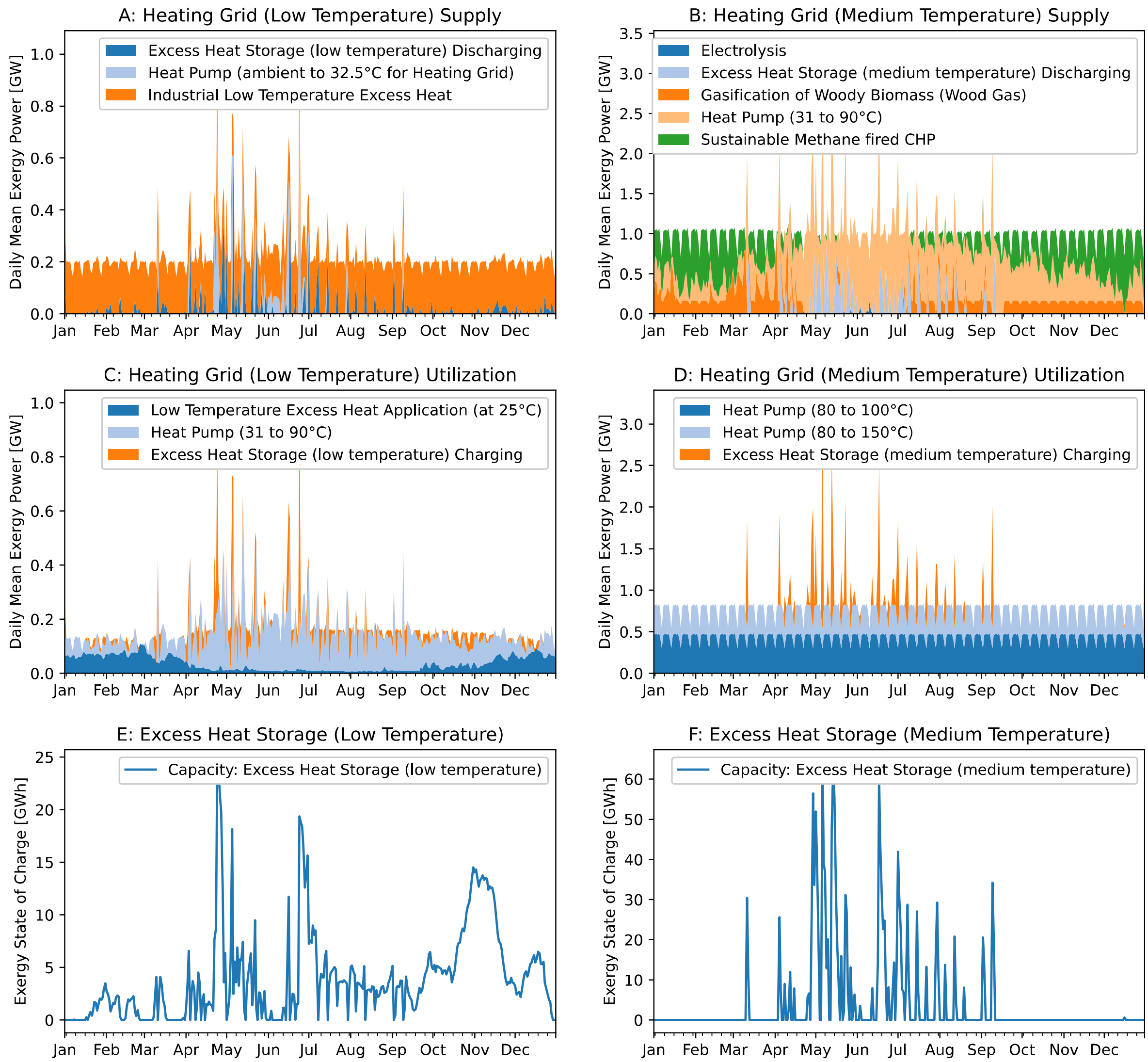

Fig. 6. Supply (A + B), utilisation (C + D) and state of charge (E + F) of the low- and medium-temperature heating grid.

(9.4 TWh/y), and electricity gird (4.9 TWh/y). For comparison, the largest exergy losses of the ESS, besides CHPs (1.4 TWh/y) and gasification (1.4 TWh/y), are caused by the kerosene production from hydrogen via Fischer-Tropsch synthesis (0.5 TWh/y). To produce kerosene from hydrogen, 19.8% of all exergy reduction are caused by exergy losses. The second highest share of losses has gasification and electrolysis (12.7%). In contrast, the district heating network (both temperature levels, incl. storages), as well as heat pumps, have a very low share of exergy losses in relation to the overall exergy reduction (less than 1%).

For final energy applications, decentralised heat pumps (17.2 TWh/y), fuel cell electric drives (12.7 TWh/y) and thermal utilisation of chemical energy (10.2 TWh/y) have the largest exergy destruction. In terms of exergy losses, ICE drives (4.5 TWh/y) and fuel cell drives (3.2 TWh/y) as well as thermal utilisation of chemical energy (2.1 TWh/y) have the highest value. Proportionally, the largest exergy losses in relation to total exergy reduction have ICE drives (61.6%), fuel cell drives (20.1%) and battery and direct electric drives (17.2%). Decentralised heat pumps and district heat exchangers have the lowest share.

The very different ratios of exergy losses and exergy destruction are caused by two basic factors: the amount of energy losses and the temperature of the energy losses. The greatest exergy losses are caused by a combination of low energy efficiency and high temperature of the losses, such as aircrafts (exhaust gas temperature: 950 °C). In contrast, in the district heating grids, the energy losses occur at a very low temperature (12 °C). Accordingly, district heating grids have almost exclusively exergy destruction. Overall, the ESS has a lower share of exergy losses in relation to the total exergy reduction (approx. 10%) compared to the FEA (approx. 17%). Most ESS conversion units are equipped with excess heat utilisation and the available excess heat is fully used. In contrast, in FEAs, excess heat utilisation is very difficult, very limited or even impossible (e.g. in transport).

Avoidable exergy destruction currently occurs in industrial plants, as exhaust gas temperatures are significantly reduced through exhaust gas cleaning and mixing with the environmental air. Higher exhaust gas temperatures (through improved processes such as appropriately designed gas cleaning and less mixing) could be used to supply a high-temperature local heating grid. By supplying appropriate exergy consumers (use of the heat at these higher temperatures), industrial exergy destruction could be

Table 3
Variation of selected parameters.

No.	Description of the variation	Parameter under investigation	Original value	Adjusted value
A	Increase in PV and Wind expansion	Generation of photovoltaics and wind power	• PV: 12.4 TWh/y • Wind: 16.0 TWh/y	• PV: 14.9 TWh/y • Wind 18.5 TWh/y
B	Decrease in PV and Wind expansion	Generation of photovoltaics and wind power	• PV: 12.4 TWh/y Wind: 16.0 TWh/y	• PV: 7.4 TWh/y Wind 11.0 TWh/y
C	Reduction of the electricity import capacity	Electricity import capacity	• 1 GW	• 0 GW
D	Power plants with single- instead of co-generation	Exergy efficiency of the excess heat output	• Sustainable Methane CHP: 0.05 • Fuel Cell CHP: 0.04 • Woody Biomass CHP: 0.13 • Wood Gas CHP: 0.12	• Sustainable Methane CHP: 0 • Fuel Cell CHP: 0 • Woody Biomass CHP: 0 • Wood Gas CHP: 0

reduced.

4. Discussion

For a proper interpretation of the results, three aspects will be discussed in this section. First, the change in the results caused by varying assumptions is analysed (subsection 4.1). Afterwards, the effect of different energy supply concepts on exergy losses and destruction are discussed (subsection 4.2). Finally, the limitations of the methodology used are presented (subsection 4.3).

4.1. Parameter variation

Selected parameters are variated to analyse the change in the results. After each variation, the modified case study is optimised ($\sum Ex = \min$) again. Four relevant parameters were identified to answer the following raising questions (Table 3):

- What happens if volatile generation expansion deviates (A, B)?
- What happens if the import of volatile electricity must be significantly reduced (C)?
- How important is co-generation and its excess heat utilisation for overall exergy efficiency (D)?

The analysis of the parameter variation results (Table 4) shows four important findings, which are independent of the considered energy system:

1. The overall exergy efficiency advantage by electrification of FEA depends on two aspects: firstly, on the exergy efficiency advantage of the electrified process compared to the classic process and secondly on the annual average electricity supply efficiency (AAESE). The AAESE considers the annual ratio r_{ConGen} of controllable generation E_{ConGen} to total electricity supply, the annual volatile generation[12] E_{VolGen}, the annual volatile electricity imports E_{VolImp}, the overall exergy efficiency of the controllable electricity generation[13] η_{ConGen} and the exergy efficiency of electricity transmission and distribution η_{Grid} (eq. (18)–(20)).

$$r_{ConGen} = \frac{E_{ConGen}}{E_{VolGen} + E_{VolImp} + E_{ConGen}} \quad 18$$

$$r_{VolGen} = 1 - r_{ConGen} \quad 19$$

$$AAESE = (r_{ConGen} \cdot \eta_{ConGen} + r_{VolGen} \cdot 1) \cdot \eta_{Grid} \quad 20$$

2. Decreasing AAESE can lead to decreasing final electricity consumption. If the AAESE is reduced while the volatile electricity generation remains the same, the residual load shifts towards negative values and might led electricity surpluses occur.
3. The AAESE is not relevant for fully controllable electricity consumers (e.g. electrolysis), as long as these are only operated with surplus electricity. The change of surplus electricity directly affects the operation of controllable electricity consumers.
4. Import capacity of electricity defines the required national volatile and controllable electricity generation capacities as well as the therefore required gas import. However, as mentioned in the first point, less volatile electricity import reduces AAESE, if it will be compensated by controllable generation.

Explanation:

Ad 1: AAESE is reduced by lower volatile electricity generation (B), reduced electricity import (C), and decreased power plant efficiency (D). However, only in case (D), AAESE decreases so much that actual shifts take place. In (D), heat supply at 150 °C is partly shifted from heat pump to incineration of woody biomass. Furthermore, in this case, a partial shift from BEV to FCEV occurs.

Ad 2,3: Less electrification but constant volatile generation (D) causes electricity surpluses. However, changes in electricity surpluses can also be caused by changing volatile generation (A, B). Changes in electricity surpluses and can be compensated by electrolysis (A, B, D).

Ad 4: Constant volatile generation and lack of import (C) is mainly compensated by an increase of the national controllable electricity generation.

4.2. Exergy losses and destruction of various energy supply concepts

In this section, the exergy losses and exergy destruction for different supply concepts are analysed. The different supply concepts cover a wide range from conventional to exergy-optimised energy systems. Each supply concept must cover the same exergy demand of electricity and heat at 65 °C (exergy ratio between electricity and heat is 1 to 0.2). The electricity can be provided by gas-fired or woody biomass fired power plants (without excess heat utilisation) or CHPs. If available, the excess heat is transported to the heat consumers via the district heating network. Decentralised gas boilers or heat pumps (using ambient heat) cover any remaining heat demand. All efficiencies, temperatures and assumptions have been chosen according to the appendix (Tables A 1, A 4–A 6 and Table A 9).[14]

This comparison (Fig. 7) shows that the use of excess heat in the

[12] Exergy efficiency = 1.
[13] Including excess heat utilisation.
[14] Exhaust gas temperature of power plants without excess heat utilisation is assumed as 300 °C.

Table 4
Results of the parameter variation. All changes compared to the results present in section 3.

No.	Change of total import	Main Consequences
A	−6.3 TWh/y	**Decrease in national electricity generation (via CHPs)** • Electricity import decreases (−4.4%/-0.3 TWh_{el}). • Less electricity generation in CHPs (−12.1%/-3.1 TWh_{el}). • Increase in electricity use for electrolysis (+278.1%/+1.0 TWh_{el}) and for heat pumps (HP ambient to 32.5 °C: +7.6%/+0.3 TWh_{el}; HP 31 to at 90 °C: +5.6%/+0.4 TWh_{el}). • Total gas import decreases (−5.6%/-5.9 TWh_{H2+SM}) since less electricity generation is required and more hydrogen via electrolysis can be provided
B	+13.3 TWh/y	**Increase in national electricity generation (via CHPs)** • Electricity import increased (+16.6%/+1.2 TWh_{el}). • Electricity generation in CHPs increased (+27.4%/+7.1 TWh_{el}). • Decrease in electricity use for electrolysis (−100%/-0.4 TWh_{el}) and for heat pumps (HP ambient to 32.5 °C: 48.4%/-0.2 TWh_{el}; HP 31 to at 90 °C: 14.1%/-1.0 TWh_{el}). Less heat from heat pumps is needed since more excess heat from the CHP is available. • Total gas import increases (+11.5%/+12.1 TWh_{H2+SM}) since more electricity is generated in CHPs and the electrolysis does not provide any hydrogen.
C	+3.2 TWh/y	**Increase in national electricity generation (via CHPs)** • No electricity import (−100%/-7.4 TWh_{el}). • Electricity generation in CHPs increased (+24.3%/+6.3 TWh_{el}). • Decrease in electricity use for electrolysis (−29.5%/-0.1 TWh_{el}) and for heat pumps (HP ambient to 32.5 °C: 13.4%/-0.05 TWh_{el}; HP 31 to at 90 °C: 12.0%/-0.8 TWh_{el}). Less heat from heat pumps is needed since more excess heat from the CHP is available. • Total gas import increases (+10.1%/+10.6 TWh_{H2+SM}) since more electricity is generated in CHPs and the electrolysis provides less hydrogen.
D	+6.6 TWh/y	**Decrease in national electricity generation (via CHPs) and shift of final exergy from electricity to chemical energy:** • Electricity import decreased (−4.4%/-0.3 TWh_{el}). • Electricity generation in power plants decreased (−5.2%/-1.4 TWh_{el}). • Heat supply up to 100 °C is still fully provided by excess heat and heat pumps. • Lack of excess heat is partly compensated by increased utilisation of heat pumps to provide heat at 90 °C (+32.2%/+2.2 TWh_{el}). The rest is compensated by the reduction in operation of the heat pump 80−150 °C (−28.5%/-2.1 TWh_{el}). • The rest of the heat demand at 150 °C is provided by incineration of woody biomass. Accordingly, decrease in woody biomass gasification (−18.1%/-5.1 TWh_{WG}). Lack of wood gas is compensated by increased incineration of imported gases. • Reduction of electricity consumption through using heavy-duty trucks with fuel cell instead of battery drive (−3.2 TWh_{el}/+4.9 TWh_{H2}). The reduced exergy efficiency of electricity generation prevails the efficiency advantage between FCEV and BEV. • Electricity for electrolysis increased (+329.3%/+1.2 TWh_{el}) due to the decreased final electricity consumption. • Total gas import increased (+6.6%/+6.9 TWh_{H2+SM}).

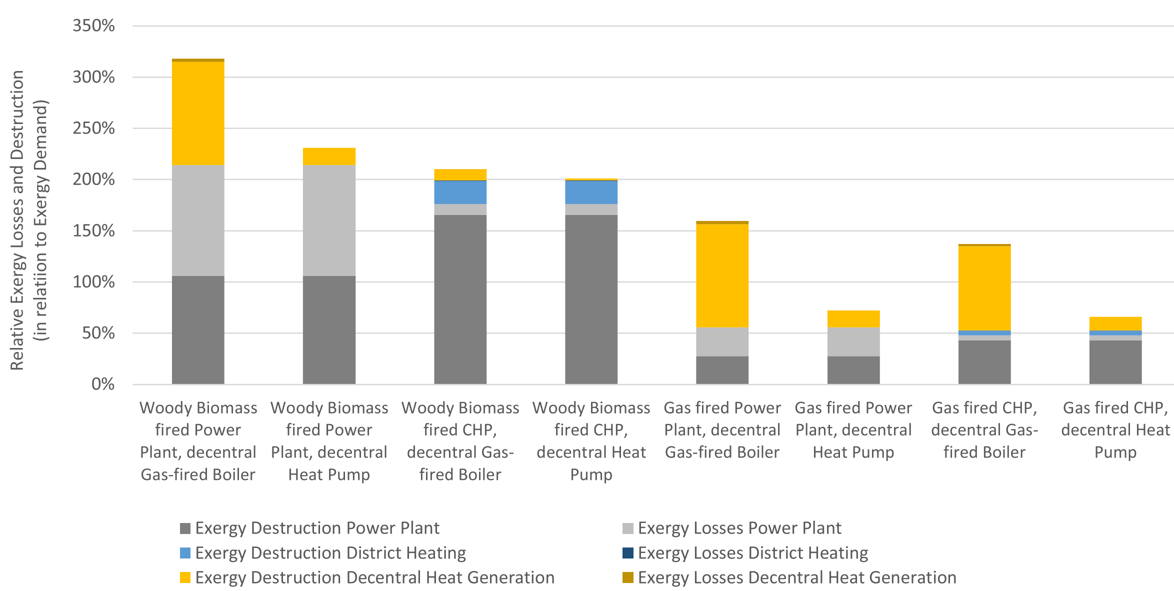

Fig. 7. Exergy Losses and Destruction of different Energy Supply Concepts.

power plant can significantly reduce exergy losses. At the same time, exergy destruction increases significantly. In addition, the district heating system leads to further exergy destruction. The exergy losses caused by the district heating system are negligible due to the low temperature. However, exergy losses and destructions of excess heat utilisation (CHP and heating grid included) are lower than the exergy losses and destruction of single generation. Otherwise, there would be no more exergy available to cover the demand (partly). It also shows that the exergy destruction of gas boilers is significantly greater than that of heat pumps. For both decentral technologies, the exergy losses are negligible. If the excess heat could be used at higher temperatures (e.g. to supply nearby industrial processes at a higher temperature level than current district heating grids), exergy destruction could be reduced even further while the losses would remain nearly unchanged.

4.3. Limitations of the methodology

The methodology used in this paper has some limitations which must be considered when interpreting the results:

- Only losses within the national borders are considered. This leads to national instead of international/global exergy efficiency (e.g. EU) since losses are shifted outside the national borders whenever possible. To include all exergy losses, alternative methods such as CExE (Cumulative Exergy Consumption) [63] must be applied. The influence of losses outside the national border must be clarified in further research.
- The model resolution does not allow any statements to be made about short-time effects (<1 day), installed power or energy grids. The actual operation can deviate significantly from the calculated daily mean power value (e.g. unit operates only a few hours per day). Accordingly, required unit sizes and capacities cannot be determined and the calculation of annual full load hours are not possible. National transmission capacities are assumed to be unrestricted, which means: expansion as needed. Limited national expansion leads to deviating results.
- In this work, many generalisations are included to consider the entire energy system, including all energy carriers and sectors. However, generalisation does not enable individual adjustments for a single system or application (e.g. most exergy efficient cooling option of CHPs is depending on regional aspects). In addition, it is not possible to include all relevant details (e.g. internal processes, piping, mass flows, or temperatures) of all systems or applications to enable a precise calculation of the exergy efficiency, exergy losses and exergy destruction. Consequently, the assumptions of the numbers used (tables in the appendix) have uncertainties.
- Despite the expansion of renewables, about half of the required exergy still must be imported. It is unclear if such large amounts of renewable energy, especially renewable gases, can be transferred to Austria. However, there are already concepts and initiatives to solve this problem of renewable hydrogen imports in the future [64].

5. Conclusion

In this work, for the first time, the interdependencies of final energy applications and the energy supply system were analysed for an entire system (including all sectors and all energy carriers). Mathematical optimisation was used to determine the optimal technology mix for maximising overall exergy efficiency. For a deeper understanding of the optimal technology mix, on one hand, a detailed investigation of the exergy losses and the exergy destruction was carried out. On the other hand, the effects of varying boundary conditions were examined within a parameter variation. In the following, the main findings as well as the final conclusions of this innovative and novel work, are presented.

The optimal technology mix could increase the total exergy efficiency of Austria from currently 34 [3] to 56%. Thereby, energy savings of about 140 TWh/y (about 38% of the current primary energy consumption in Austria) can be achieved. The Austrian degree of self-sufficiency can be raised to 51%. Despite a significant expansion of volatile electricity generation including a high degree of electrification, gaseous chemical energy carriers do not lose their importance. Gases are essential for both ESS and FEA since they cover 52% of the primary exergy consumption and 42% of the final exergy demand.

The most important technology changes for final energy applications are in the areas of heat supply and transport. Heat supply up to 150 °C can be entirely covered by using excess heat (both, medium and low-temperature), heat pumps and, if necessary, ambient heat. Incineration of chemical energy carriers is used at higher temperature levels. For land transport, electric drive systems (BEV or overhead wiring) show the highest efficiency. If there no overhead wiring is available or battery electric drive is not feasible, FCEVs are used. The efficiency of e-fuels is much lower than comparable BEVs or FCEVs for land transport. Therefore, e-fuels should only be used in aviation due to a lack of alternatives.

Strong electrification of final energy applications (+44% compared to 2018 [49]) and massive expansion of renewable electricity generation (+58% compared to 2018 [49]) requires a flexible energy supply system. Large controllable electricity generation capacities are needed to cover the seasonal variation of volatile generation and the high space heating demand in winter. All power plants should be designed as CHPs to increase energy efficiency. The occurring negative electricity residual loads can be fully utilised with district heating supplying heat pumps plus short and medium time heat storages and electrolysis. However, the national hydrogen production covers only a small part of the total consumption (less than 0.5%).

This work clearly shows that when considering electrification both aspects must be taken into account: energy efficiency improvement of the electrified process compared to the conventional process as well as the annual average electricity supply efficiency (AAESE). Accordingly, low AAESE (e.g. caused by inefficient power plants) can prevent shifts from chemical energy-based to electricity-based applications from an exergy efficient point of view. For example, the parameter variation analysis showed that in the case of inefficient power plants, the FCEV is preferable over BEVs for heavy-duty trucks.

The use of modern technologies and the complete utilisation of excess heat result in very low exergy losses. Thereby two effects are important. On one hand, modern technologies such as BEVs or heat pumps have significantly lower energy loss temperatures compared to ICE drives or incineration processes. On the other hand, excess heat utilisation usually increases the share of exergy destruction since the excess heat temperature is usually significantly lower than the unused waste flow's temperature. This could be prevented by additional local heating networks with higher temperatures than usual. For such grids, it is important to connect mainly heat consumers which required such a high temperature level. Otherwise, only higher energy losses will occur in the heating grid (due to higher temperatures) but the same exergy destruction will take place (but at final energy application instead of the excess heat source). However, this needs to be investigated in detail in further research.

Author statement

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Abbreviations in general

AAESE	Annual Average Electricity Supply Efficiency
BEV	Battery Electric Vehicle
CExE	Cumulative Exergy Consumption
CHP	Combined Heat and Power
COP	Coefficient of Performance
CUED	Current Useful Exergy Demand
ESS	Energy Supply System
el	Electricity
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FEA	Final Energy Application
H2	Hydrogen
HP	Heat Pump
ICE	Interal Combustion Engine
ICT	Information and Communication Technology
MES	Multi Energy System
PEC	Primary Energy Consumption
SM	Sustainable Methane
th	Thermal Energy or Exergy
WB	Woody Biomass
WG	Wood Gas

Symbols used in equations

$C_{j,i}$	Exergy conversion efficiency of exergy of energy carrier *i* to exergy of exergy carrier *j*
E_{ConGen}	Controllable Electricity Generation
E_{VolGen}	Volatile Electricity Generation
E_{VolImp}	Volatile Electricity Import
En_i	Energy of flow *i*
En_{In}	Total energy input
$En_{Loss,k}$	Energy Loss flow *k*
$Ex_{CU,In,i}$	Exergy input flow of a conversion unit of type *i*
$Ex_{CU,Out,i}$	Exergy output flow of a conversion unit of type *i*
$Ex_{CU,Out,i,j}$	Exergy output flow of conversion unit *i* to cover CUED of category *j*
$Ex_{CUED,j}$	Current useful exergy demand of category *j*
$Ex_{CUED,tot}$	Total CUED over all categories
Ex_{Dest}	Exergy destruction
$Ex_{Exp,k}$	Exergy export *k*
Ex_i	Exergy of flow *i*
ΔEx_i	Exergy charged or discharged of storage *i*
$Ex_{Imp,j}$	Exergy import *j*
$Ex_{In,i}$	Exergy input flow *i* of a bus
$Ex_{Loss,k}$	Exergy loss flow *k*
$Ex_{LossDest,Cha,i}$	Exergy losses and destruction of storage *i* during by charging
$Ex_{LossDest,\ DisCha,i}$	Exergy losses and destruction of storage *i* during by discharging
$Ex_{LossDest,\ OT,i}$	Exergy losses and destruction of storage *i* over time
$Ex_{LossDest,tot}$	Total exergy losses and destruction
$Ex_{Sup,tot}$	Total exergy used for supply
$Ex_{Out,i}$	Exergy output flow *i* of a bus
$Ex_{Sink,i}$	Exergy flow to sink *i*
$Ex_{Source,i}$	Exergy flow from source *i*
$f_{C,i}$	Carnot factor of flow *i*
$f_{Ex,i}$	Exergy factor of flow *i*
$r_{i,j}$	Ratio of exergy outflow of conversion unit *i* to the total CUED of category *j*
$r_{Ex,Loss,k}$	Relative exergy loss of flow *k* in relation to the total exergy input
$r_{Ex,Dest}$	Relative exergy destruction in relation to the total exergy input
r_{ConGen}	Share of controllable electricity generation in relation to total electricity generation
r_{VolGen}	Share of volatile electricity generation in relation to total electricity generation
SOC_i	State of charge of storage *i*
T_0	Temperature of the environment
T_i	Temperature of the medium *i*
η_{ConGen}	Exergy efficiency of the controllable electricity generation
$\eta_{En,CU,j}$	Energy efficiency of energy output *j* to total energy input of a conversion unit
$\eta_{Ex,CU,j}$	Exergy efficiency of exergy output *j* to total exergy input of a conversion unit
η_{Grid}	Exergy efficiency of electricity transmission and distribution

Appendix A

In the appendix, all exergy efficiencies, the share of exergy losses and the share of exergy destruction are listed for all technologies included in this work (Tables A 1–A 11). In addition, these tables contain all additional information to be able to reproduce the resulting values. For calculation, see subsections 2.2.1 and 2.2.2. Furthermore, Table A 12 contains a list of direct consumers that require exergy to cover the process demand. These do not show any efficiency, as the exergy is consumed there (passive system).

Table A 1
Exergy conversion efficiency, exergy losses and exergy destruction of CHPs

Type	Energy Efficiency of Electricity	Energy Efficiency of Useable Excess Heat	Overall Energy Efficiency	Temperature of Unusable Exhaust Gas and Useable Excess Heat in °C	Exergy Efficiency of Electricity	Exergy Efficiency of Useable Excess Heat	Exergy Destruction	Exergy Losses
Woody Biomass fired CHP (Clausius-Rankine-Cycle)	0.270 [35,65]	0.580	0.850	92	0.270	0.130	0.566	0.034
Wood Gas fired CHP (ICE)	0.300 [66]	0.550	0.850	92	0.300	0.124	0.543	0.034
Fuel Cell CHP (PEM)	0.600 [37]	0.200	0.800 [37]	92	0.600	0.045	0.310	0.045
Sustainable Methane fired CHP (Combined Cycle)	0.600 [67,68]	0.250	0.850 [67]	92	0.600	0.056	0.310	0.034

Table A 2
Exergy conversion efficiency, exergy losses and exergy destruction of conversion processes for providing renewable gases (hydrogen, methane, wood gas)

Type	Energy Efficiency of Conversion	Energy Efficiency of Useable Excess Heat	Overall Energy Efficiency	Temperature of Unusable Exhaust Gas and Useable Excess Heat in °C [B]	Exergy Efficiency of Conversion	Exergy Efficiency of Useable Excess Heat	Exergy Destruction	Exergy Losses
Water Electrolysis (PEM)	0.700 [38]	0.150	0.850	92	0.700	0.034	0.233	0.034
Methanation of Hydrogen to Sustainable Methane	0.800 [69]	0.050	0.850	92	0.800	0.011	0.155	0.034
Gasification of Woody Biomass to Wood Gas plus Methanation to Sustainable Methane	0.560 [A]	0.290	0.850	92	0.560	0.065	0.341	0.034
Gasification of Woody Biomass to Wood Gas	0.700 [70]	0.150	0.850	92	0.700	0.034	0.233	0.034

[A] Gasification of woody biomass to wood gas (energy conversion efficiency 70% [70]) and afterwards methanation (energy conversion efficiency 80% [71]).
[B] Feed-in temperature of the district heating grid.

Table A 3
Exergy conversion efficiency, exergy losses and exergy destruction of conversion processes for providing renewable fuels (kerosene, biodiesel)

Type	Energy Efficiency of Conversion	Temperature of Unusable Exhaust Gas	Exergy Efficiency of Conversion	Exergy Destruction	Exergy Losses
Production of Kerosene or Diesel from Hydrogen via Fischer-Tropsch-Synthesis	0.769 [72]	80	0.769	0.185	0.046
Production of Kerosene or Diesel from Sustainable Methane via Reforming and Fischer-Tropsch-Synthesis	0.650 [72]	80	0.650	0.281	0.069

Table A 4
Exergy transmission efficiency, exergy losses and exergy destruction of electricity and district heating gird (without heat exchangers)

Type	Energy Efficiency of Transport	Temperature of Energy Losses in °C	Exergy Efficiency of Transport	Exergy Destruction	Exergy Losses
Electricity Grid	0.953 [49]	80 [B]	0.953	0.038	0.009
District Heating Grid (92 [D] to 90 °C [E]; return at 30 °C) [C]	0.968	12 [A]	0.949	0.050	0.000
District Heating Grid (85 [D] to 80 °C [E]; return at 31 °C) [C]	0.907	12 [A]	0.859	0.140	0.001
District Heating Grid (34 [D] to 32.5 °C [E]; return at 15 °C) [C]	0.921	12 [A]	0.868	0.132	0.001
District Heating Grid (31 [D] to 27.5 °C [E]; return at 15 °C) [C]	0.781	12 [A]	0.659	0.340	0.002

[A] At a ground temperature of 6 °C, the district heating pipe has an outside temperature of about 12 °C [73].
[B] Typical maximum Temperature of power grids.
[C] Both, the energy loss due to cooling (and the associated exergy losses) as well as the exergy destruction caused by the reduction of temperature are included.
[D] Temperature at the place of feed-in.
[E] Temperature at the place of use.

Table A 5
Exergy conversion efficiency, exergy losses and exergy destruction of final energy applications for covering heat demand via district heating (only heat exchanger considered)

Type	Energy Efficiency of the Heat Supply	Flow Temperature of Heating Grid °C	Overall Exergy Efficiency of Heat Supply	Overall Exergy Destruction	Overall Exergy Losses
District Heating Application at 25 °C	1.000	80	0.254	0.746	0.000
District Heating Application at 65 °C	1.000	80	0.821	0.179	0.000
District Heating Application at 25 °C	1.000	27.5	0.864	0.136	0.000

Table A 6
Exergy conversion efficiency, exergy losses and exergy destruction of heat pumps

Type	Energy Efficiency [A]	Heat Pump Quality Factor	Overall Exergy Efficiency [B]	Overall Exergy Destruction	Overall Exergy Losses
Heat Pump (31–90 °C)	1.000	0.500 [74]	0.593	0.407	0.000
Heat Pump (80–100 °C)	1.000	0.500 [74]	0.849	0.151	0.000
Heat Pump (80–150 °C)	1.000	0.500 [74]	0.714	0.286	0.000
Heat Pump (between ambient and from 25 up to 150 °C)	1.000	0.500 [74]	0.500	0.500	0.000

[A] energy losses are neglected based due the energy balance of a heat pump: $\dot{Q}_{Out,\ Hot} = \dot{Q}_{In,Cold} + P_{el}$.

[B] calculated via footnote before, eq. (9) and the following relation: $1/f_{Carnot} \cdot factor_{quality} = COP_{real} = \frac{\dot{Q}_{Out,hot}}{P_{el}}$ [74].

Table A 7
Exergy efficiency, exergy losses and exergy destruction of storages

Type	Energy Efficiency (only Inflow/ Outflow)	Exergy Efficiency (only Inflow/ Outflow)	Exergy Destruction (only Inflow/ Outflow)	Exergy Losses (only Inflow/ Outflow)	Energy Efficiency per day (without Inflow/Outflow)	Exergy Efficiency per day (without Inflow/Outflow)	Exergy Destruction per day (without Inflow/Outflow)	Exergy Losses per day (without Inflow/ Outflow)	Temperature of Unused Heat Losses in °C
Battery Electric Storages (Lithium – Ion)	0.900 [36]	0.900	0.089	0.011	1.000	1.000	0.000	0.000	45 [E]
Hydrogen Storage	0.950	0.950	0.033	0.017	1.000	1.000	0.000	0.000	150 [D]
Sustainable Methane and Wood Gas Storage	0.980	0.980	0.018	0.002	1.000	1.000	0.000	0.000	50
Kerosene and Ethanol fuel/ Biodiesel Storage	0.980	0.980	0.018	0.002	1.000	1.000	0.000	0.000	50
Thermal Storage (Medium Temperature) [A]	1.000	0.951	0.049	0.000	0.973	0.954	0.044	0.003	16 [C]
Thermal Storage (Low Temperature) [A]	1.000	0.938	0.062	0.000	0.986	0.974	0.025	0.001	12 [B]
Woody Biomass Storage	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	–

[A] The following exergy losses and destructions are considered: the exergy losses due to cooling over time, the exergy destruction due to the temperature reduction caused by cooling and the exergy destruction caused by temperature differences between feed-in/feed-out and the actual average storage temperature.
[B] Outside temperature of district heating grid pips are taken ([73]) since low temperature storages are often built in the ground.
[C] Same temperature difference as the low temperature thermal storage between outside temperature to ground (6 K) assumed, but based on the average air temperature of Austria (10 °C).
[D] Maximum temperature of hydrogen compression.
[E] Temperature based on optimal electronic and battery temperature.

Table A 8
Exergy conversion efficiency, exergy losses and exergy destruction of final energy applications for covering transport demand

Type	Energy Efficiency of Refuelling	Temper-ature of Refuelling Losses in °C	Energy Efficiency of Engine	Energy Share of Engine's Excess Heat in Exhaust Gas/Coolant [D]	Temper-ature of Exhaust Gas/ Coolant in °C [D]	Electrical Energy Efficiency (Temp. of the Losses: 40 °C)	Mechanical Energy Efficiency (Temp. of the Losses: 80 °C) [G]	Propulsion Energy Efficiency (Temp. Of the Losses: 10 °C)	Overall Exergy Efficiency for Movement	Overall Exergy Destruction	Overall Exergy Losses
BEV - Cars and Light Duty Trucks	0.901 [75]	45	0.950 [76]	0.000/1.000	-/45	0.930 [E]	0.950	0.980	0.741	0.229	0.030
BEV - Heavy Duty Trucks	0.901 [75]	45	0.950 [76]	0.000/1.000	-/45	0.930 [E]	0.950	0.970	0.734	0.236	0.030
Electric Locomotives	1.000	45	0.950 [76]	0.000/1.000	-/45	0.970 [F]	0.950	0.995	0.871	0.111	0.018
FC - Locomotives	0.940 [A]	150 [J]	0.570 [B]	0.100/0.900	80/75	0.970 [F]	0.950	0.995	0.491	0.406	0.103
FC - Cars and Light Duty Trucks	0.920 [77]	150 [J]	0.523 [C]	0.100/0.900	80/75	0.970 [F]	0.950	0.980	0.434	0.451	0.115
FC - Heavy Duty Truck (long-distances)	0.940 [A]	150 [J]	0.570 [B]	0.100/0.900	80/75	0.970 [F]	0.950	0.980	0.484	0.413	0.103
FC - Ship	0.940 [A]	150 [J]	0.570 [B]	0.100/0.900	80/75	0.970 [F]	0.950	0.560 [H]	0.276	0.621	0.103
Airplanes	1.000	–	0.356	1.000/0.000	950/-	0.995	0.950	0.820 [I]	0.276	0.225	0.499
ICE - Cars and Light Duty Trucks	1.000	–	0.300	0.571/0.429	300/90	0.995	0.915	0.980	0.268	0.459	0.274
ICE - Heavy Duty Truck	1.000	–	0.330	0.571/0.429	300/90	0.995	0.915	0.970	0.291	0.446	0.263
ICE - Ship	1.000	–	0.330	0.571/0.429	300/90	0.995	0.915	0.560 [H]	0.168	0.569	0.263
ICE - Locomotive	1.000	–	0.330	0.571/0.429	300/90	0.995	0.915	0.995	0.299	0.438	0.263

[A] Calculation based on [77], but lower pressure considered (350 bar instead of 1000 bar).
[B] Fuel cell efficiency (large, higher number of full load hours) of 0.6 and electric motor efficiency of 0.95 [76].
[C] Fuel cell efficiency (small, lower number of full load hours) of 0.55 and electric motor efficiency of 0.95 [76].
[D] Based on test bench measurements by HyCentA.
[E] Energy losses of battery is (4%) and energy losses of power electronics (3%) considered [76]. Temperature based on optimal electronic and battery temperature.
[F] Energy losses electronics (3%) considered [76].
[G] Average mechanical energy efficiency for ICE with gearbox is 91.5%, most efficient mechanical energy efficiencies are 95% according to [78]. Temperature assumption based on the design of the components in the drive train.
[H] Energy efficiency of propulsion for transport ship and inland water vessel is about 44% [79].
[I] Energy efficiency of propulsion for Turbofan aircrafts is about 80% (during flight) [80].
[J] Maximum temperature of hydrogen compression.

Table A 9
Exergy conversion efficiency, exergy losses and exergy destruction of final energy applications for covering heat demand via incineration or electric direct heating

Type	Energy Efficiency of the Heat Supply [A]	Temperature of Unused Heat Losses in °C [B]	Overall Exergy Efficiency of Heat Supply	Overall Exergy Destruction	Overall Exergy Losses
Heat Supply at 25 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.850	150	0.0428	0.9076	0.0496
Heat Supply at 65 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.850	150	0.1383	0.8120	0.0496
Heat Supply at 100 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.850	150	0.2051	0.7453	0.0496
Heat Supply at 150 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.850	150	0.2813	0.6690	0.0496
Heat Supply at 250 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.850	200	0.3901	0.5497	0.0603
Heat Supply at 400 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas) or Electric Direct Heating	0.850	200	0.4926	0.4472	0.0603
Heat Supply at 750 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas) or Electric Direct Heating	0.850	200	0.6149	0.3249	0.0603
Heat Supply at 1500 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas) or Electric Direct Heating	0.850	300	0.7143	0.2098	0.0759

[A] Average value is based on the analysis of different industrial plants in Styria, Austria [81].
[B] Value is based on the analysis of different industrial plants in Styria, Austria [81].

Table A 10
Exergy conversion efficiency, exergy losses and exergy destruction of LED lights, electric compressor and variable-frequency drive

Type	Energy Efficiency	Temperature of Unused Heat	Overall Exergy Efficiency	Overall Exergy Destruction	Overall Exergy Losses
LED Light	0.137 [82]	50	0.131 [82]	76%	11%
Electric Compressor for Gas Pipelines	0.840 [83]	13 [A]	0.840	16%	0%
Variable-Frequency Drive (Electric Engine)	0.880 [84]	150 [B]	0.880	8%	4%

[A] warming of the gas calculated via adiabatic compression (typical pressure ration <1.4 [83]).
[B] assumed via NEMA insulation classes for motors [85].

Table A 11
Exergy conversion efficiency, exergy losses and exergy destruction of industrial CHP with direct excess heat usage

Type	Energy Efficiency of Provision of Shaft Work	Energy Efficiency of Useable Excess Heat	Overall Energy Efficiency	Temperature of Unusable Exhaust Gas in °C [A]	Exergy Efficiency of Provision of Shaft Work	Exergy Efficiency of Useable Excess Heat	Overall Exergy Destruction	Overall Exergy Losses
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 25 °C	0.500 [86]	0.350	0.850	200	0.500	0.018	0.422	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 65 °C	0.500 [86]	0.350	0.850	200	0.500	0.057	0.383	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 100 °C	0.500 [86]	0.350	0.850	200	0.500	0.084	0.355	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 150 °C	0.500 [86]	0.350	0.850	200	0.500	0.116	0.324	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 250 °C	0.500 [86]	0.350	0.850	200	0.500	0.161	0.279	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 25 °C	0.300 [66]	0.550	0.850 [66]	200	0.300	0.028	0.612	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 65 °C	0.300 [66]	0.550	0.850 [66]	200	0.300	0.089	0.550	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 80 °C	0.300 [66]	0.550	0.850 [66]	200	0.300	0.109	0.531	0.060

(continued on next page)

Table A 11 (*continued*)

Type	Energy Efficiency of Provision of Shaft Work	Energy Efficiency of Useable Excess Heat	Overall Energy Efficiency	Temperature of Unusable Exhaust Gas in °C [A]	Exergy Efficiency of Provision of Shaft Work	Exergy Efficiency of Useable Excess Heat	Overall Exergy Destruction	Overall Exergy Losses
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 100 °C	0.300 [66]	0.550	0.850 [66]	200	0.300	0.133	0.507	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 150 °C	0.300 [66]	0.550	0.850 [66]	200	0.300	0.182	0.458	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 250 °C	0.300 [66]	0.550	0.850 [66]	200	0.300	0.252	0.387	0.060

[A] Assumption based on the analysis of different industrial plants in Styria, Austria [81].

Table A 12
Covering Process Demands

Process Demand (Without Conversion)
Hydrogen for Direct Reduction of Iron Ore in Crude Steel Production
Electricity for Electric Arc Furnace in Crude Steel Production
Methane/Hydrogen for Non Energy Use (use of gases as a raw material and not as an energy source, e.g. in the chemical industry for ammonia production)
Electricity for Electrochemical Production Processes such as Electroplating or Electrogalavanizing
Electricity for Information and Communication Technology

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Third Journal Article

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Table A 3. Author statement to the third journal article

Activity	**Contributing authors (the first-mentioned is the main author)**
Conceptualisation	C. Sejkora, J. Lindorfer, T. Kienberger
Methodology	C. Sejkora, J. Lindorfer, T. Kienberger
Data curation	C. Sejkora, J. Lindorfer, L. Kühberger
Software development and validation	C. Sejkora
Modelling	C. Sejkora, J. Lindorfer
Investigation and analysis	C. Sejkora, J. Lindorfer, L. Kühberger
Visualization	C. Sejkora, J. Lindorfer
Writing (original draft)	C. Sejkora, J. Lindorfer, L. Kühberger
Writing (review and editing)	C. Sejkora, T. Kienberger, J. Lindorfer

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Article

Interlinking the Renewable Electricity and Gas Sectors: A Techno-Economic Case Study for Austria

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Abstract: Achieving climate neutrality requires a massive transformation of current energy systems. Fossil energy sources must be replaced with renewable ones. Renewable energy sources with reasonable potential such as photovoltaics or wind power provide electricity. However, since chemical energy carriers are essential for various sectors and applications, the need for renewable gases comes more and more into focus. This paper determines the Austrian green hydrogen potential, produced exclusively from electricity surpluses. In combination with assumed sustainable methane production, the resulting renewable gas import demand is identified, based on two fully decarbonised scenarios for the investigated years 2030, 2040 and 2050. While in one scenario energy efficiency is maximised, in the other scenario significant behavioural changes are considered to reduce the total energy consumption. A techno-economic analysis is used to identify the economically reasonable national green hydrogen potential and to calculate the averaged levelised cost of hydrogen ($LCOH_2$) for each scenario and considered year. Furthermore, roll-out curves for the necessary expansion of national electrolysis plants are presented. The results show that in 2050 about 43% of the national gas demand can be produced nationally and economically (34 TWh green hydrogen, 16 TWh sustainable methane). The resulting national hydrogen production costs are comparable to the expected import costs (including transport costs). The most important actions are the quick and extensive expansion of renewables and electrolysis plants both nationally and internationally.

Keywords: power to gas; electrolysis; green hydrogen; national potential; decarbonisation; scenario analysis; national energy system; techno-economic analysis; levelised cost of hydrogen

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1. Introduction

The EU Green Deal [1] aims for climate-neutrality of the European continent by 2050. This goal requires a fundamental transformation of the energy system since fossil sources like natural gas and oil must be replaced by renewable ones. One central point of the Green Deal is the massive expansion of renewable energy plants [2,3]. The massive expansion in renewable electricity generation is intended to be used for the direct electrification (e.g., heat pumps, electric vehicles) and the indirect electrification (e.g., renewable hydrogen in industrial processes and long-range freight transport) of the European energy system [3].

However, for several sectors (e.g., long-range freight transport or iron and steel making), currently there does not exist an economically viable option for decarbonisation [4]. In total, all sectors that have currently no economic decarbonisation option account for about one-third of the total energy-related CO_2 emissions. However, hydrogen could enable the decarbonisation of these sectors in the future [5]. In their review, Hanley et al. [6] identified several drivers for hydrogen, such as large renewable generation capacities, decarbonisation in general, cost-efficient decarbonisation of sectors that are otherwise difficult to decarbonise (e.g., freight) and lack of development for carbon capture and storage (CCS). In the publications they investigated, a variety of possible applications for hydrogen were found. For example, the use of hydrogen in the field of transport (e.g., [7,8]), in the field of industry (e.g., [9]) or in the field of energy supply (e.g., [10]) has been recently examined.

In addition to broad applicability, hydrogen enables decoupling between volatile generation and controllable energy supply [5]. Furthermore, it is suitable for seasonal energy storage. For long storage periods such as summer to winter, it is more cost-effective to store hydrogen instead of electricity in batteries [11]. The importance of hydrogen for the energy transition has been highlighted in various publications based on its advantages and versatility (e.g., [12–14]). Furthermore, according to the comprehensive review by Kovač et al. [15] energy transition strategies without hydrogen do not have the potential for achieving full CO_2 neutrality.

BloombergNEF and the Hydrogen Council are expecting hydrogen to account for up to 24% and 18% of global final energy consumption in 2050, respectively [16,17]. The production of such large quantities of hydrogen can be achieved by different production routes. A nomenclature based on different colours is now widely used to distinguish between them [18,19]:

- Grey hydrogen: Production of hydrogen via steam methane reforming of methane or gasification of coal. Thereby, CO_2 emissions are emitted into the atmosphere. Thus, grey hydrogen is not an option for a decarbonised energy supply.
- Blue hydrogen: It uses the same production process as grey hydrogen but includes carbon capture and storage (CCS). This technology raises additional costs for the transport and storage of CO_2. However, CCS can only reduce CO_2 emissions up to 95% but not eliminates them.
- Turquoise hydrogen: Pyrolysis of methane is used to produce hydrogen and solid carbon black. Storage of solid carbon black is easier than storage of gaseous CO_2 (blue hydrogen). Alternatively, carbon could also be used in industry and agriculture as raw materials.
- Pink hydrogen: Use of water electrolysis to produce hydrogen. The required electrical energy is provided by nuclear power plants.
- Green hydrogen: Renewable energy is used to produce hydrogen. Several processes are available. However, the most important process for the production of green hydrogen is the electrolysis of water, supplied by renewable electricity. The electrolysis of water can be implemented as a zero-emissions route. In this work, green hydrogen always refers to this process.

Decarbonised energy systems can in principle be based on blue, turquoise, pink or green hydrogen. However, pink hydrogen should be viewed critically, as the final disposal of nuclear waste is still unclear. Blue and turquoise hydrogen rely on natural gas with the associated problem of leakage. For example, the total US-wide methane losses are estimated to be about 1.3% of the overall transported methane [20]. Methane has an 84–86 or 28–34 times higher global warming potential compared to CO_2 within the first 20 or 100 years after release, respectively [21]. In addition, in Europe, acceptance problems of blue hydrogen exist, but it can be seen as a bridging technology until green hydrogen becomes widely available [18]. Currently, the production costs of green hydrogen are about 2 to 3 times higher than of grey hydrogen [12]. In the long term, green hydrogen is the hydrogen type of choice for a fully decarbonised energy system.

For reaching the 1.5 °C global warming target, the EU will have an annual hydrogen demand between 1536 and 1953 TWh in 2050 [22], according to the EU's long-term strategy [23]. Due to the enormous renewable electricity demand required to produce this amount of hydrogen, imports of green hydrogen will probably be necessary in addition to European production of green hydrogen [24]. Eventually, various European countries such as Germany [24] or Austria [25] do not have accessible renewable potentials to cover their current national primary energy demand.

Many different studies address hydrogen production costs on a national or regional level. Such studies can include a lot of detail, such as regional characteristics. The study by Agora Verkehrswende, Agora Energiewende and Frontier Economics [26] and their associated calculation tool [27] analyses the production costs of power to hydrogen, power to methane and power to liquid for different regions. For example, according to their calculation tool [27], in 2050, the cost of hydrogen production from offshore wind turbines at North and Baltic Seas would range from 6.0 to 11.8 €ct/kWh$_{H2}$, depending on the scenario (pessimistic to optimistic). In contrast, the costs of hydrogen from geothermal energy in Iceland were calculated between 3.5 and 4.3 €ct/kWh$_{H2}$. Both examples include operating and investment costs of electrolysis, electricity costs, lifetime as well as expected full-load hours. The considered full-load hours are equal to the full-load hours of the respective renewable source. Thus, the entire electrical generation is used for hydrogen production.

However, an integrated consideration of the entire energy system (all sectors, all energy carriers, from resource to energy service) is important to obtain meaningful results. Such a holistic consideration is necessary for the calculation of the actual residual loads. The residual load is the not controllable electricity demand minus the not controllable electricity generation. Not controllable generations are fluctuating generations such as photovoltaics as well as heat-driven CHPs. If the not controllable electricity generation is higher or lower than the not controllable electricity demand, it is known as negative or positive residual load, respectively. The positive residual load must be compensated by controllable electricity generation (e.g., gas-fired power plants) or discharging of electricity storages. The negative residual load can be handled by renewable generation reduction or can be used for different applications, such as the production of hydrogen. To maximise the overall efficiency of the energy system, mainly negative residual load should be used for hydrogen production. For example, this approach was used to analyse the annual hydrogen production in Italy [28]. Otherwise, avoidable conversion losses will occur (production of hydrogen and controllable electricity generation at the same time).

The amount of negative residual load strongly depends on the renewable generation. A low amount of electricity available for electrolysis (e.g., due to a low amount of negative residual loads) might lead to a low number of full-load hours. This increases hydrogen costs [12]. Therefore, a hydrogen production cost analysis should include the negative residual loads and their temporal characteristics.

The current Austrian government programme [29] aims for complete decarbonisation by 2040. However, there is currently no comprehensive decarbonisation strategy of Austria available. Although no such strategy is yet in place, hydrogen is expected to play a central role according to the current political discussion. In this context, many essential aspects (e.g., national demand of hydrogen, national hydrogen production potential or the hydrogen import demand) have not yet been clarified. Nevertheless, these aspects are mandatory for such a strategy. As a step towards a comprehensive decarbonisation strategy of Austria, this study provides such insights regarding the national hydrogen situation. Since these insights have not been published in any study we found, the following research questions are investigated for Austria:

1. How will the Austrian green hydrogen potential for negative residual loads develop between 2030 and 2050?
2. Which part of this potential can be economically realised? What are the resulting levelised costs of hydrogen ($LCOH_2$)?
3. Which share of the national renewable gas demand can be covered by national green hydrogen production? How much renewable gas imports are necessary?

To answer the research questions, the entire Austrian energy system, including all sectors and all energy carriers, is analysed. Based on two scenarios, possible trends until 2050 are depicted. Both scenarios aim for full decarbonisation and consider the same renewable expansion till 2050. However, there are major differences in consumption and technologies used: The scenario *Energy Efficiency* relies on the optimal mix of novel technologies to maximise energy efficiency. In contrast, the scenario *Sufficiency* is based on conventional technologies in combination with massive behavioural changes (sufficiency measures). Based on negative residual loads of both scenarios, the potential of hydrogen production by water electrolysis was assessed and related $LCOH_2$ was quantified for cost structures expected for 2030, 2040 and 2050.

Answering the research questions using the mentioned approach provides a valuable contribution to scientific knowledge. The contribution consists of two aspects: methodology and results. In this work, entire national energy system models (including all sectors and all energy carriers) are used. Entire national energy system models such as EnergyPLAN [30] are common in the scientific literature and include both technical and economic aspects. The analysis of such models is often used for feasibility studies of national decarbonisation strategies (e.g., [31–34]). Furthermore, different pathways can be compared to determine the minimum cost of decarbonisation. These studies do include hydrogen, but it is not the focus of the research questions. In addition to this, there are also studies that investigate hydrogen and its production in detail but do not take all sectors into account (e.g., [28,35]). Thereby, negative residual loads are used to determine the hydrogen production. Since not all sectors are considered, the residual load does not include the electrification of the other sectors that may be necessary to enable complete decarbonisation (e.g., heat pumps or battery electric vehicles). Furthermore, no statements can be made about the total gas demand in the future system. This work combines both types of studies: The focus is on hydrogen potential and costs, but in the background the complete energy system and the complete decarbonisation strategy is considered. Such a combination has not been seen before and represents a further development and improvement of existing approaches.

In addition to the methodological novelty, the results of this study are interesting for the scientific community. On the one hand, answering these questions for Austria can act as a blueprint for countries with similar structures. On the other hand, such national studies can be an important basis for supra-regional research analyses (e.g., EU-wide or worldwide).

This work is structured as follows: First, within the methodology (Section 2), the determination approach of the potential of nationally produced green hydrogen as well as its techno-economic assessment is shown. Next, the results are presented (Section 3) and discussed (Section 4). Within the discussion, the feasibility of the results is analysed. Furthermore, the resulting $LCOH_2$ is compared with the production costs of other publications (considering green hydrogen, grey hydrogen, blue hydrogen and import of green hydrogen). Finally, Section 5 concludes the entire work.

2. Methodology

The methodology of this work is structured as follows (Figure 1): Firstly, the trend in the expansion of the national renewable energy generation is discussed (I). Secondly, two different consumption scenarios are presented (II-A and II-B). These two scenarios differ fundamentally in how the national full decarbonisation goal can be achieved. While scenario *Energy Efficiency* focuses on the optimal mix of novel technologies, scenario *Sufficiency* focuses on sufficiency measures. Thirdly, the time-resolved energy consumption per energy carrier of both scenarios is combined with the national renewable energy generation/production (III). Thereby the determination of the Austrian green hydrogen production potential via electrolysis per scenario is performed. Fourthly, these national green hydrogen potentials are techno-economically assessed to calculate the economic green hydrogen potential per scenario (IV). The technical and economic potentials are calculated for the considered years 2030, 2040 and 2050. Finally, performance indicators are identified, such as the primary energy consumption, the economic green hydrogen potential and the required renewable gas imports, and their temporal development is analysed for both scenarios (V).

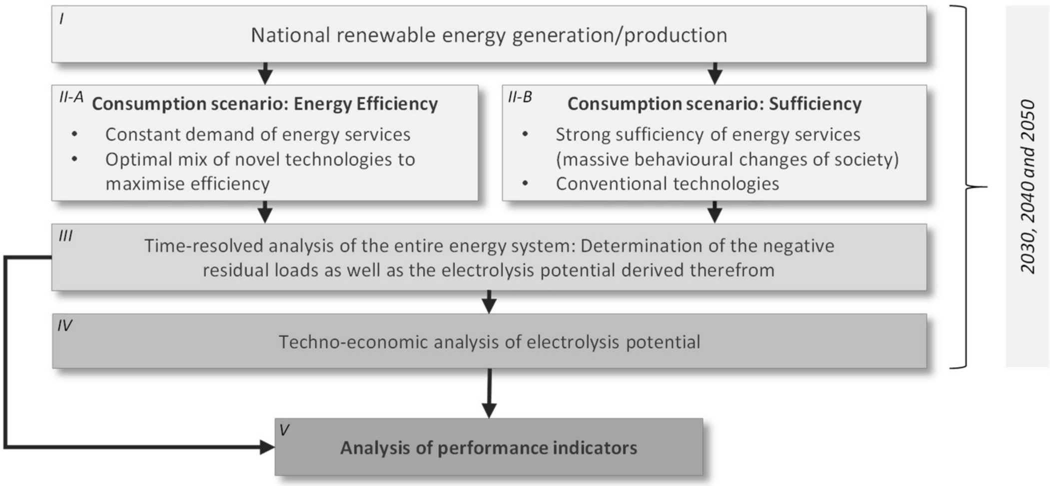

Figure 1. Flow chart of the methodology.

2.1. National Potential of Green Hydrogen Production

In this subsection, the approach for the determination of the national technical potential of green hydrogen is presented, which addresses steps I to III of Figure 1. First of all, the system boundaries of the applied energy system model are defined. It can be divided into three blocks (Figure 2):

1. The national renewable generation/production of various energy carriers.
2. The national energy conversion, transportation and distribution system, which connects the first and the third block.
3. Different final energy applications for covering all national energy services from all economic sectors. Such energy services might be space heating, process heat, lighting or mobility.

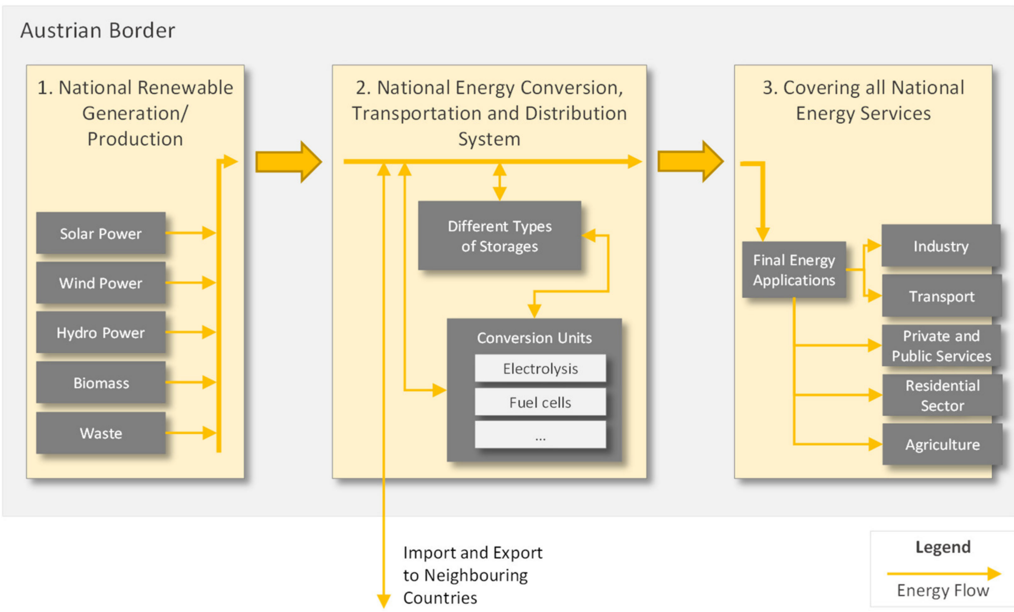

Figure 2. System boundaries of the Austrian energy system model.

In this model (Figure 2), the renewable generation/production and the required energy services are defined by boundaries conditions. Thus, the renewable generation/production can never exceed the predefined amounts and temporal behaviour, and all predefined energy services must always be covered. The national energy conversion, transportation and distribution system must compensate all temporal differences between renewable generation/production and final energy applications. Furthermore, the required type (e.g., electricity, heat or fuel) of final energy has to be provided. To achieve this, different controllable conversion units, storages as well as import/export to neighbouring countries can be used.

Various controllable applications are possible for utilising the negative residual loads such as charging of electricity storages, operation of electrolysis and supply of district heating grids via operation of central heat pumps or transport to neighbouring countries. In this work, only negative residual loads are used to determine the green hydrogen potential, but not all of them. Other energy carriers such as biomass are used for other purposes (e.g., heat supply) as well as for controllable renewable electricity generation to compensate the positive residual loads. The specific use of the negative residual loads are discussed in detail for each scenario individually.

For meaningful modelling, various aspects such as modelling scope, time horizon or spatial coverage must be considered [36]. A bottom-up approach is used to consider technological details. An operational model was chosen to ensure the consideration dynamics of supply and demand. Accordingly, time horizon and temporal resolution must correspond. In energy systems with a large share of renewable generation, annual, weekly and short-time fluctuations occur [37]. To consider all these fluctuations, a time-resolved analysis for a period of one year with a temporal resolution of hourly values is selected. The research questions are focused on Austria but do not include any spatially resolved aspects, such as grids. Thus, the spatial coverage is Austria without taking any spatial resolution into account. In the scenario *Energy Efficiency*, model formulation is based on a linear optimisation problem with the assessment criteria of maximum exergy efficiency. In contrast, the other scenario is arranged as a simulation task with linear formulation with specifications of the final energy consumption. Both scenarios ensure full decarbonisation for each considered year.

In the following, first, the renewable generation/production (1. block) is discussed in Section 2.1.1. Next, the two scenarios are presented in detail in Sections 2.1.2 and 2.1.3. These two scenarios include both, the national energy conversion, transportation and distribution system (2. block) as well as the final energy applications to cover the energy services (3. block).

2.1.1. Renewable Generation/Production

In this subsection, the boundary conditions of the renewable generation/production are discussed. Renewable generation/production (Table 1) is the same for both scenarios. The expansion of fluctuating renewable generation (photovoltaics, wind power and hydro power) as well as for sustainable methane production (e.g., from biogas plants) is based on the 2030 targets from the current Austrian government programme [29] and continues linearly until 2050. The renewable generation of the year 2018 according to Statistics Austria is used as starting point for the expansion [38]. The current government programme [29] does not specify any expansion plans for woody biomass, ethanol fuel or biodiesel (from energy crop cultivation). Accordingly, the production of 2018 [38] is assumed to remain constant until 2050, as no significant increase is expected based on the current land use. However, additional expansion potential is theoretically available [25,39]. The trend of renewable generation of solar thermal energy and the availability of waste is defined by the Environmental Agency Austria (EAA) [40]. According to the EAA, the available waste for energy use will decrease until 2050. Normalized load profiles are multiplied by the annual generation/production sum to create supply time series.

Table 1. Renewable generation/production.

Type	Value 2030 in TWh/a	Value 2040 in TWh/a	Value 2050 in TWh/a	Extrapolated Generation/Production Profile
Photovoltaic Systems	12.4	21.6	30.7	Generation from photovoltaic in Austria 2018 [41]
Wind Power Stations	16.0	24.3	32.7	Generation from wind in Austria 2018 [41]
Hydropower Plants	42.6	46.8	50.9	Generation from hydro in Austria 2018 [41]
Solar Thermal System	5.7	5.7	7.3	Generation from photovoltaic in Austria 2018 [41]
Woody Biomass Production	41.9	41.9	41.9	Assumed as constant based on current situation
Sustainable Methane Production	7.7	12.9	16.1	Assumed as constant based on current situation
Ethanol Fuel/Biodiesel Production	2.3	2.3	2.3	Assumed as constant based on current situation
Waste	9.0	8.2	7.0	Assumed as constant based on current situation

2.1.2. Scenario Energy Efficiency

In this scenario, no behavioural changes are taken into account. Instead, the reduction in primary energy consumption is only achieved by increasing national energy efficiency by means of an optimal mix of novel technologies. For this purpose, an exergy-based optimisation model with a linear formulation is used. In contrast to energy-based analysis, exergy as assessment criteria for maximising energy efficiency also includes the quality of energy. The quality of the energy describes the technical working capacity [42]. Since exergy is not a conservation variable, the cause of exergy reduction between input and output of a process can enable deeper insights. A distinction is made between exergy losses (exergy in unused waste flows such as exhaust gas) and exergy destruction (reduction of working capacity due to thermodynamic imperfections) [43]. In addition to the additional understanding of the location and cause of the exergy reduction, an exergy-based approach is necessary for energy systems including primary energy sources with different exergy levels. In this case, exergetic optimisation provides exergetically better results than an exclusively energetic optimisation. For this reason, the optimisation performed in this scenario is based on exergy.

The approach used takes into account the entire energy system and minimises the total of exergy losses and exergy destruction, whether they occur in the energy conversion, transformation and distribution systems or in the final energy applications (Figure 2). The holistic approach is crucial to also include the interaction between final energy applications and the energy conversion, transportation and distribution systems. For example, an electrified final application (e.g., battery electric vehicle) may have a worse overall efficiency than the conventional final application (e.g., internal combustion engine vehicle) when including the electricity provision (e.g., old and inefficient coal powered power plant).

For modelling this problem, a greenfield approach is chosen to find the best energy system without considering existing structures. The optimisation model used is based on the Open Energy Modelling Framework (*oemof*) [44,45]. The mathematical formulation of the optimisation model and further information of *oemof* can be found in the official documentation [46]. However, one important adaptation of *oemof* was made for this work. An additional constraint was introduced—that the ratio of the different final energy applications to each other must be constant for the entire optimisation period. This prevents redundant final energy applications. An example of redundant final energy applications would be that each vehicle owner has two or more vehicles, such as a battery electric car that is only driven when enough electricity is available (in summer) and a hydrogen vehicle that is otherwise used (in winter). Since this is unrealistic, it is prevented by an additional constraint. In contrast, for the energy conversion, transportation and distribution system the various technologies are redundantly available and can be used flexibly in order to maximise exergy efficiency.

In this scenario, the Austrian demand for energy services is determined by the useful exergy demand. It describes the actually required thermodynamic working demand of the useful energy. The optimization model must cover all specified useful exergy demands, while not exceeding the specified renewable resources. Between the generation- and demand-related boundary conditions, the mix, capacities and operation of various conversion units, storage and final energy applications are optimized to maximise overall energy efficiency (Figure 2). In addition, import/export of various energy carriers is possible.

Exergy efficiencies of all technologies describe the conversion of the input exergy to the output exergy. If a technology has several outputs (e.g., CHP), the total exergy efficiency can be determined from the sum of the individual efficiencies (e.g., power output in relation to the input as well as heat output in relation to the input). A complete list of all efficiencies can be found in Appendix A.1. The overall efficiency depends on the (time-resolved) operation and combination of the technologies used and the associated conversion chains. Maximising energy efficiency means minimising the total of exergy losses and exergy destruction $Ex_{LossDest,tot}$. It be calculated based on the total useful exergy demand of all national energy services $Ex_{UED,tot}$ and the total exergy used for supplying the national energy system $Ex_{Sup,tot}$ (Equation (1)). $Ex_{Sup,tot}$ is defined as the sum of all national renewable generation/production $Ex_{NatGP,i}$ and the balance of all exergy imports $Ex_{Imp,j}$ and exports $Ex_{Exp,k}$.

$$\min Ex_{LossDest,tot} = Ex_{Sup,tot} - Ex_{UED,tot} = \sum_i Ex_{NatGP,i} + \left(\sum_j Ex_{Imp,j} - \sum_k Ex_{Exp,k} \right) - Ex_{UED,tot} \quad (1)$$

The final objective function minimises the total of exergy losses and exergy destruction (Equation (1)). However, the national renewable production/generation and the total useful exergy demand are given as constraints (boundary conditions) of the optimisation task. Therefore, they can be neglected as optimisation variable. Accordingly, the objective function simplifies (Equation (2)). Thus, the exergy efficiency of an energy system can be maximised by minimising exergy imports and maximising exergy exports for a given national demand and national renewable generation/production. In order to increase national self-sufficiency, export is only possible if all national potential/production is used in the entire optimisation period.

$$\min f = \sum_j Ex_{Imp,j} - \sum_k Ex_{Exp,k} \quad (2)$$

The exergy-based optimisation model described here for the analysis of a national energy system in currently under review by the authors of this work [47]. Further information can be found there when it is published.

Approach for the utilisation of negative residual loads: The national green hydrogen potential is a direct result of the previously explained optimisation task. By minimising the exergy losses and exergy destruction, it is also determined when negative residual loads are mathematically optimally used for hydrogen production and when they are better used for other purposes. However, this multiple use of negative residual loads reduces the national green hydrogen potential as well as the full-load hours of the electrolysis.

In this scenario, only photovoltaic systems, wind power plants and hydro power plants are not controllable electricity sources (block 1 in Figure 2). All storages and conversion units of the energy conversion, transportation and distribution system (block 2 in Figure 2) are controllable (these are hydro pumped storages, battery storages, electrolyses plants, supply of district heating grids via central heat pumps), while all final electricity applications (e.g., battery electric vehicles, single decentral heat pumps per building, industrial stationary engines) are considered not controllable (block 3 in Figure 2).

Used data: As mentioned before, in this scenario the useful exergy demand is used to define the need for energy services. The useful exergy demand for 2030, 2040 and 2050 is based on the Austrian current useful exergy demand, which has already been published by the authors [25]. These data include all economic sectors (industry, residential, transport, private and public services as well as agriculture) as well as all statistically considered energy service classes of Austria (heat demand at different temperature levels between 25 and 1500 °C, transport demand of cars, light-duty trucks, heavy-duty trucks, railways, navigation, aviation, stationary work engines, lighting, information and communication technology as well as process demands). However, these demands are adjusted for economic growth (until 2030: +1.5% p.a., after 2030 +1.3% p.a. [40]) as well as the decrease in energy intensity (current value of −1.4% p.a. assumed [48]). The only change compared to the useful exergy demand published in [25], efficiencies adopted and to achieve full decarbonisation, the blast furnace route for crude steel production is replaced by a direct reduction process including an electric arc furnace. All used data and additional information about this scenario can be found in Appendix A.1.

2.1.3. Scenario *Sufficiency*

The scenario *Sufficiency* is based on renewable generation/production according to Table 1 as well as on the work of the Environment Agency Austria (EAA). The EAA published different possible future development energy scenarios for the Austrian energy system until 2050 [49] to satisfy the report requirements according to EU regulation No. 525/2013 [50]. All these EAA scenarios consider the entire energy system, from resource to energy service for all subordinated economic sectors (e.g., industry, residential sector, transport) and energy carriers. Furthermore, import and export are included. The EAA scenarios differ mainly in their assumptions regarding the implementation of energy efficiency and novel technologies as well as behavioural changes of society. Overall, the EAA scenarios cover a wide range from business as usual to very radical changes. The scenario *Sufficiency* in this work is based on the EAA scenario WAMplus (With Additional Measures Plus), which is the most ambitious scenario and strongly relies on sufficiency measures.

The storyline of the EAA scenario WAMplus describes a turning away from the current consumer society and includes resource-efficient concepts such as green economy and sharing economy. Accordingly, in the industry sector, the highly efficient use of resources and energy are assumed. Furthermore, the number of products produced will be reduced, which leads to a further decrease in energy use. However, due to the shift to high-value, durable and long used products, the value of production remains nearly constant. In the transport sector, the modal split is changing strongly towards environmentally-friendly transport modes (e.g., freight traffic by railway, increased usage of public transport). A strong reduction of motorised individual transport is assumed. The shift away from the consumer society is reducing the transport volume. The thermal renovation of buildings is another key measure. In the energy sector, the extension of renewable electricity production and district heating plays are relevant. Further details about the EAA scenario WAMplus can be found in [40].

The EAA scenario WAMplus is not decarbonised. It includes the use of fossil energy carriers such as oil, coal and natural gas. To reach the aim of full decarbonisation, in this paper the following approach is applied to the energy consumption specified in the EAA scenario WAMplus: Firstly, we calculated all actual energy service demand required by society for all economic sectors (e.g., total annual driving distance, total annual production of crude steel, heat demand for space heating) based on the assumptions and results of the WAMplus scenario. Subsequently, the final energy applications to be used for decarbonisation were determined. In the next step, by combining both, the actual energy service demand and the efficiency of the decarbonised final energy applications, the final energy consumption of the decarbonised energy system could be calculated. Finally, adaptions and decarbonisation of the energy conversion, transportation and distribution system were required to balance generation and supply (e.g., electricity generation, district heating supply).

In contrast to scenario *Energy Efficiency*, the decarbonisation strategy of this scenario is based mainly on conventional technologies. Consequently, only small technological changes are required, and large parts of the existing infrastructure can be further used. The most important measures are explained in the following:

Fossil fuels (e.g., coal, fuel oil, natural gas) for space and process heating as well as stationary engines in the residential, public and private services sectors as well as agriculture are fully replaced by renewable gases. Furthermore, also in the district heating supply, renewable gases replace natural gas entirely.

In this scenario, transport is based on both internal combustion engines (ICEs) and electric drives. To decarbonise ICE drives, renewable fuels are used. Renewable fuels are hydrocarbon-based fuels from sustainable sources, e.g., produced from atmospheric carbon dioxide and hydrogen from water electrolysis, supplied with renewable electricity. They are also known as electrofuels [51]. The share of battery electric vehicles (BEVs) over the years [40] is multiplied by the maximum possible amount of BEV, in accordance with the required range and transport capacity [47]. In general, these assumptions can be considered as rather conservative. For railways, electrification is assumed following the EAA scenario WAMplus. The rest of transport (including aviation and navigation) is entirely covered by renewable fuel powered ICE drives.

For the decarbonisation of the industrial sector, the *current infrastructure usage* scenario according to a recent study by Baumann et al. [52] is used. This study is based on a combination of top-down and bottom-up approaches to properly describe the decarbonisation of all industrial subsectors. For the application in this paper, the energy consumptions are adjusted according to the scenario assumptions of the EAA scenario WAMplus (e.g., annual production volume).

Approach for the utilisation of negative residual loads: In addition, in this scenario, the national potential of green hydrogen is calculated based on negative residual loads. For determining them, the not controllable generation in this scenario consists of photovoltaics, wind power plants, hydro power plants, electricity generation of industrial CHPs (8400 full-load hours a year assumed), utilization of waste in CHPs (8400 full-load hours a year assumed) and woody biomass CHPs (8000 full-load hours a year assumed). In this scenario, the total electricity consumption is not controllable, except for the operation of electrolysis as well as charging of pumped storage power plants and battery storage systems. Accordingly, this scenario has the same controllable consumption as the scenario *Energy Efficiency*, except for the central heat pumps.

The pumped storage power plants and battery storages are operated according to a greedy algorithm. This algorithm charges the storage whenever negative residual load occurs and discharges at positive residual loads. The only limitations are the storage capacities as well as the charging and discharging powers. The rest of the negative residual load can be used to determine the green hydrogen potential. All used data and additional information about this scenario can be found in Appendix **??**.

2.2. Techno-Economic Assessment of National Green Hydrogen Production

This analysis is used to determine the national economic potential for green hydrogen (Section 2.1), as well as their approximate energy production costs as levelized costs of hydrogen ($LCOH_2$). The analysis is based on the annuity method [53] and applied as described by Böhm et al., 2020 [54].

To determine the levelised costs of an energy product, all costs and proceeds are related to the energy output to be produced. The annuity of total annual payments A is calculated as the difference between the annuity of proceeds from by-product sales A_P and the sum of the annuities of capital-related A_C, demand-related A_D, operation-related A_O and other costs A_M (Equation (3)):

$$A = A_P - (A_C + A_D + A_O + A_M) \tag{3}$$

With the annuity and demand related variable costs C_{var}, one can calculate the $LCOH_2$ as described in Equation (4), with $P_{H2,y}$ as the annual hydrogen production [55].

$$LCOH_2 = \frac{-A + \sum_{y=1}^{n} C_{var,y}}{\sum_{y=1}^{n} P_{H2,y}} \quad (4)$$

In Table 2, all input parameters including the cost structures for the electrolysis reference plants for the techno-economic assessment are listed. For the economic evaluation, the electricity procurement costs for the electrolysis operation are derived from a mix of wind and PV generation costs and electricity grid tariffs/charges, based on optimal conditions and cross-checked with other prognoses on electricity prices [56]. In the medium and long term, decreasing electricity production costs from renewables is to be expected (Table 2) [54,57].

Table 2. Cost structures of the electrolysis reference plants.

Type	Unit	2020	2030	2040	2050
General					
Interest	%	4.0	4.0	4.0	4.0
Life time	Years	20	20	20	20
Electricity cost [1]	€/MWh_{el}	50	40	35	30
Electrolysis					
CAPEX	€/kW_{el}	944 [2]–1527 [3]	510 [2]–983 [3]	572 [2]–250 [3]	477 [2]–200 [3]
El. efficiency (LHV)	%	60	64	67	68
OPEX	% of CAPEX	4	3	2	2
Power requirement for auxiliary units	% of nominal power	1	1	1	1
Cost water	€/$m^3 H_2O$	1.15	1.15	1.15	1.15
Lifetime stack	Hours	40,000	60,000	100,000	140,000
Lifetime BoP	Years	30	30	30	30
Usable heat	% of nominal power	16	16	16	16
Additional costs					
Insurance	% of CAPEX	0.5	0.5	0.5	0.5
Management	% of CAPEX	2	2	2	2
Proceeds					
Heat	€/MWh_{th}	55	55	55	55
Oxygen	€/t_{O2}	50	50	50	50

[1] Constant electricity purchase prices assumed (mix of wind and PV levelised cost of electricity (LCOE)); electricity grid tariffs and charges based on Austrian framework 2020; [2] reference plant scaling 1 MW_{el}; [3] reference plant scaling 100 MW_{el}.

The electrolyser plant accounts for significant investment cost (CAPEX) with plant-specific variability in electrolyser stack, potential H_2 compressor, storage, dispenser needs and supplement factors for the balance of a plant. Accordingly, learning curve and scale effects are also taken into account for these components in the calculations for the economic evaluation. The former considers the future reduction in production costs for these plant components through increasing experience in the manufacturing process (see electrolyser CAPEX development Table 2). This technological learning thus describes those cost reductions that can be expected from the increase in cumulative production and thus from the optimization of manufacturing processes and material use. In addition, spillover effects from concurrent technology uses such as electrical installation and control systems may also be relevant. A disaggregated learning curve model for analysing technological learning at the component level allows these aspects to be taken into account accordingly [58]. In addition to learning curves, scale effects are relevant. In addition to cost reductions by increasing the number of units produced ("economies of manufacturing scale"), the scaling of the respective electrolysis also has a significant influence on the specific investment costs ("economies of unit scale") [54].

For taking into account economies of scale, we use a mix of representative reference plant scalings. The scalings correspond to the economic data reference on component cost structures and corresponding scale factors [54] resulting in large scale industrial facilities. The reference plants are differentiated into small plants with a power range between 1 and 10 MW_{el}, medium plants between 10 and 50 MW_{el} and large plants between 50 and 100 MW_{el}. Cost transformations through innovation (efficiency, durability, design), plant size (targeting up to 100 MW_{el}), component assembly lines and gigafactories will be needed to reach the anticipated roll-out curve of electrolyser plants, although there are hardly any plants of this size on the market, and there is little operating experience at the moment. For each year, a plant mix based on these reference plants was generated that can optimally process the previously calculated negative residual loads that are available for electrolysis. The ramp-up of the theoretical electrolysis potential is based on a CAGR (Compound Annual Growth Rate) of 25% [59] in the years 2020–2050 for all reference plants in line with corresponding press releases in this area, whereby the required ramp-up is massive and the forecast horizon is clearly a very long one and therefore highly uncertain.

Techno-economic analysis procedure: First of all, the $LCOH_2$ for each specific possible number of full-load hours of hydrogen, the considered years 2030, 2040 and 2050 as well as three different plant sizes are calculated, based on Equation (4) and Table 2. By using this comprehensive table, the threshold of economic full-load hours for each considered year and plant size, based on maximal $LCOH_2$, was defined. In this work, the maximum $LCOH_2$ economic limit is 15 €ct/kWh_{HHV}, based on hydrogen's cost competitiveness evaluation in recent literature [60–63]. In addition, the influence of this value is analysed within the discussion of this work (Section 4.1).

In the next step, the maximum number of economic full-load hours are analysed in combination with the negative residual loads available for green hydrogen production. For each considered year, the number of full-load hours is determined for each possible power of the residual load (between 0 and its maximum power in 0.01 MW_{el} steps). If the number of full-load hours of a certain power is equal to the economic full-load hours determined in the first step, the maximum economic power limit is found. This power limit represents the maximum economic electrolysis power (in GW_{el}). This analysis is performed for both scenarios and all the considered years. The maximum electrolysis power determined in this way ensure that the previously defined maximal $LCOH_2$ economic limit for hydrogen is not exceeded.

Then, the theoretical expansion plan is developed based on the defined electrolytic reference plant mix. On this basis, the required yearly installations were quantified in the timeframe of 2020 to 2050.

Finally, the electrolysis power and the corresponding green hydrogen production forecasts are used to determine the final averaged $LCOH_2$ per scenario and considered year (Equation (4) with the parameters from Table 2). For this purpose, the $LCOH_2$ for different full-load hours must be evaluated, which are then averaged according to the actual production volume per full-load hour range.

2.3. Performance Indicators

The following performance indicators (Table 3) were identified to enable a comparison of the two scenarios and their temporal development until 2050. All indicators consider annual totals and refer to Austria as a whole.

Table 3. List of performance indicators.

Performance Indicator	Unit	Description
Primary energy consumption	TWh/a	Sum of national renewable generation/production and all energy imports
Final energy consumption	TWh/a	Sum of all energy flows for finale energy applications
Renewable energy generation and production	TWh/a	Sum of all renewable energy generation and production (including all renewable sources of Table 1)
Total negative residual loads	TWh_{el}/a	Total amount of fluctuating renewable electricity generation not required for any other electrical application or any storage facility
Lower limit for full-load hours of electrolyser plants	h/a	Minimum full-load hours required in order not to exceed the maximum $LCOH_2$ economic limit
Installed electrolysis capacity	GW_{el}	Total size of the economic electrolysis plants
Negative residual loads used for electrolysis	TWh_{el}/a	Amount of negative residual loads used for green hydrogen production
Share of negative residual loads used for electrolysis	%	Share of all technical negative residual loads used for national economic green hydrogen production, based on the techno-economic analysis
Technical green hydrogen production	TWh_{H2}/a	Technical green hydrogen output from electrolysis, produced exclusively by utilization of negative residual loads
Economic green hydrogen production	TWh_{H2}/a	Economic green hydrogen output from electrolysis, produced exclusively by utilization of negative residual loads
Total consumption of renewable gases	TWh/a	Sum of national produced and imported hydrogen as well as sustainable methane
Required import of renewable gases (based on technical potentials)	TWh/a	Sum of imported hydrogen and sustainable methane (considers the national technical potentials)
Required import of renewable gases (based on economic potentials)	TWh/a	Sum of imported hydrogen and sustainable methane (considers the national economic potentials)
Share of technical national renewable gas production	%	Ratio of the national green hydrogen and sustainable methane production to the total consumption of renewable gases
Averaged levelised cost of national produced green hydrogen	$€ct/kWh_{HHV}$	Levelised cost for hydrogen production averaged over the entire annual hydrogen production volume
Minimal levelised cost of national produced green hydrogen	$€ct/kWh_{HHV}$	Minimal levelised cost for hydrogen production per year (large plant with high number of full-load hours)
Maximal levelised cost of national produced green hydrogen	$€ct/kWh_{HHV}$	Maximal levelised cost for hydrogen production per year (small plant with low number of full-load hours)

3. Results

The results of this work are presented in four sections. Firstly, the two scenarios are discussed from the energy point of view (Section 3.1). This includes the comparison of primary and final energy consumption, the resulting residual load as well as the negative residual loads usable for electrolysis. Then the results of the techno-economic analysis are shown (Section 3.2). The latter consists of different aspects such as the economic green hydrogen potential, the resulting averaged $LCOH_2$ as well as the number of electrolyser plants in Austria. In the next step, the import demand for renewable gases is examined (Section 3.3). Finally, performance indicators are used to summarise all results of both scenarios and their temporal development (Section 3.4).

3.1. Energy-Based Results

Comparison of the primary energy consumption: The primary energy consumption of the two scenarios for all years is shown in Figure 3. The comparison shows that the scenario *Energy Efficiency* has a lower consumption than the other scenario for each considered year. The difference is mainly caused by the utilisation of renewable gases. Both scenarios have a decreasing renewable gas consumption over the years, but scenario *Sufficiency* starts at a significantly higher level. The utilisation of electricity, solar thermal energy as well as biomass and waste are comparable for both scenarios. The electricity consumption increases over the years in both scenarios.

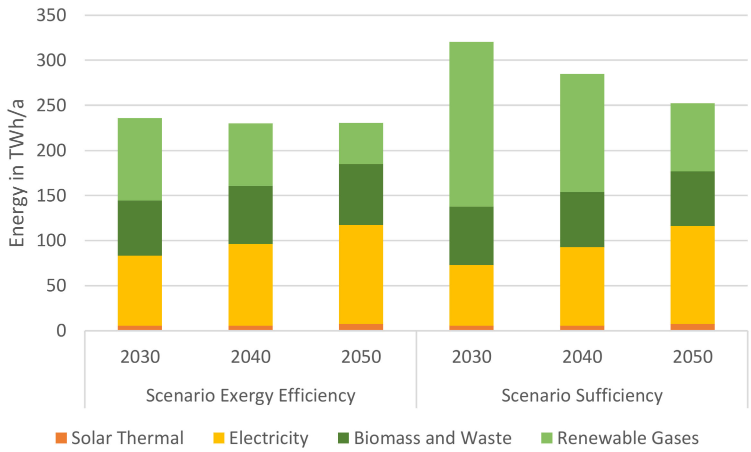

Figure 3. Comparison of the primary energy consumption for both scenarios and all considered years.

Explanations of the difference in primary energy consumption: For both scenarios, the decreasing primary energy consumption can be explained by the scenario assumptions. The assumed technological development leads to a reduction of the primary energy consumption due to better energy efficiencies independent of the scenario. In scenario *Energy Efficiency*, energy intensity (energy consumption in relation to GDP) decreases and over-compensates economic growth. As a result, primary energy consumption decreases over time (Figure 3). In the other scenario, increased behavioural changes lead to a massive decrease in the demand for energy services over the years. Thus, primary energy consumption is reducing. The significantly higher consumption of renewable gases in scenario *Sufficiency* is caused by exergetically inefficient technologies such as renewable gases for space heating instead of highly exergy efficient technologies such as heat pumps. Furthermore, renewable gases are also used for providing renewable fuels to supply internal combustion engine (ICE) drives for road transport. In addition to inefficient ICE drives, this conversion causes further losses. The comparable temporal development of electricity, biomass and waste, as well as for solar thermal energy can be explained by the same assumed renewable generation/production for both scenarios (Section 2.1.1). Increasing renewable generation over the years leads to a higher primary energy consumption of the associated energy carrier (e.g., electricity). In both scenarios, solar thermal energy as a primary energy source plays a minor role.

Comparison of the final energy consumption: The final energy consumption (Figure 4) shows clear differences in the consumption structures between the two scenarios: Compared to the scenario *Sufficiency*, scenario *Energy Efficiency* has significantly higher final energy consumption of solar thermal and district heating, electricity as well as renewable gases. In contrast, the scenario *Sufficiency* has a higher consumption of biomass and waste, as well as renewable fuels.

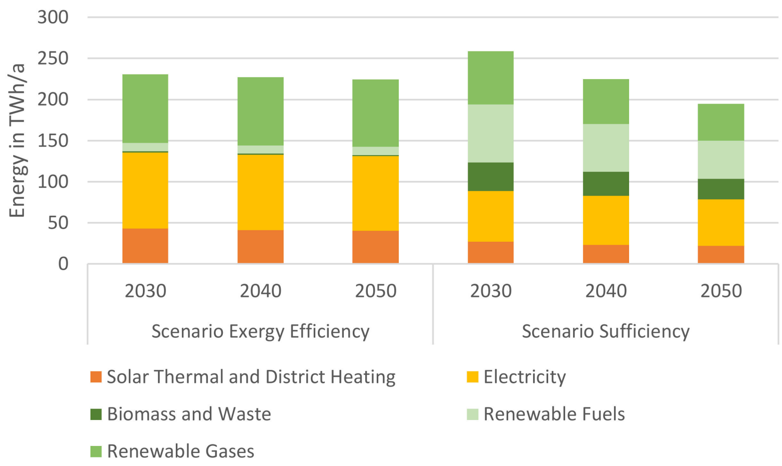

Figure 4. Comparison of the final energy consumption for both scenarios and all considered years.

Explanations of the difference in final energy consumption: These different consumption structures can be explained by the different scenario narratives. The scenario *Energy Efficiency* relies exclusively on the most energy-efficient technologies, which leads to strong structural changes compared to the current energy system: Transport consists mainly of electric and fuel cell drives (fuel cell drives are only used if electric drives are not feasible, e.g., due to the required range). Aviation is supplied with renewable fuels, due to the lack of other available technologies. In heat supply, all heat up to 150 °C is provided exclusively by excess heat and heat pumps. Incineration of woody biomass is only used for covering the demand at 250 °C. Heat demands at higher temperatures are covered by the incineration of renewable gases. A detailed discussion of the optimal technology mix to maximise Austria's exergy efficiency can be found here in [47].

In contrast, the scenario *Sufficiency* does not include major changes in the consumption structure compared to the current situation in Austria (Section 2.1.3). Only electric mobility is slowly reducing the share of internal combustion engines over the years, and fossil energy sources are mainly replaced by renewable alternatives (renewable gases and fuels). Thus, the differences to the scenario *Energy Efficiency* in final exergy consumption can be explained by the lower electrification, lower excess heat utilisation, still a significant share of combustion engines in transport, as well as the utilisation of biomass for space heating.

Comparison of the residual loads: In a time-resolved analysis of the residual loads, differences between not controllable generation and not controllable consumption can be shown. Residual loads are particularly relevant for the electrical energy system, as electricity storing is only possible to a limited extent (e.g., limited capacity of pumped storage power plants). Accordingly, only the electrical residual loads are discussed in the following.

The residual loads of the scenario *Energy Efficiency* show more positive values in both winter and summer than the scenario *Sufficiency* (Figure 5). This is also indicated by the maximum annual positive residual load (2030: 13.0 compared to 5.4 GW_{el}; 2040: 12.4 compared to 4.9 GW_{el}, 2050: 11.8 compared to 4.4 GW_{el}). In total, positive residual loads for the scenario *Energy Efficiency* sum up to 27, 17 and 11 TWh_{el}/a for the considered years 2030, 2040 and 2050, respectively. In contrast, in the scenario *Sufficiency*, the accumulated positive residual load is much lower (2030: 6 TWh_{el}/a, 2040: 3 TWh_{el}/a, 2050: 1 TWh_{el}/a). Positive residual loads must always be compensated by controllable plants. When analysing negative residual loads, both scenarios show comparable maximum negative values for each year. However, scenario *Energy Efficiency* has significantly negative residual loads for each considered year (2030: −6 compared to −13 TWh_{el}/a; 2040: −18 compared to −33 TWh_{el}/a, 2050: −35 compared to −54 TWh_{el}/a).

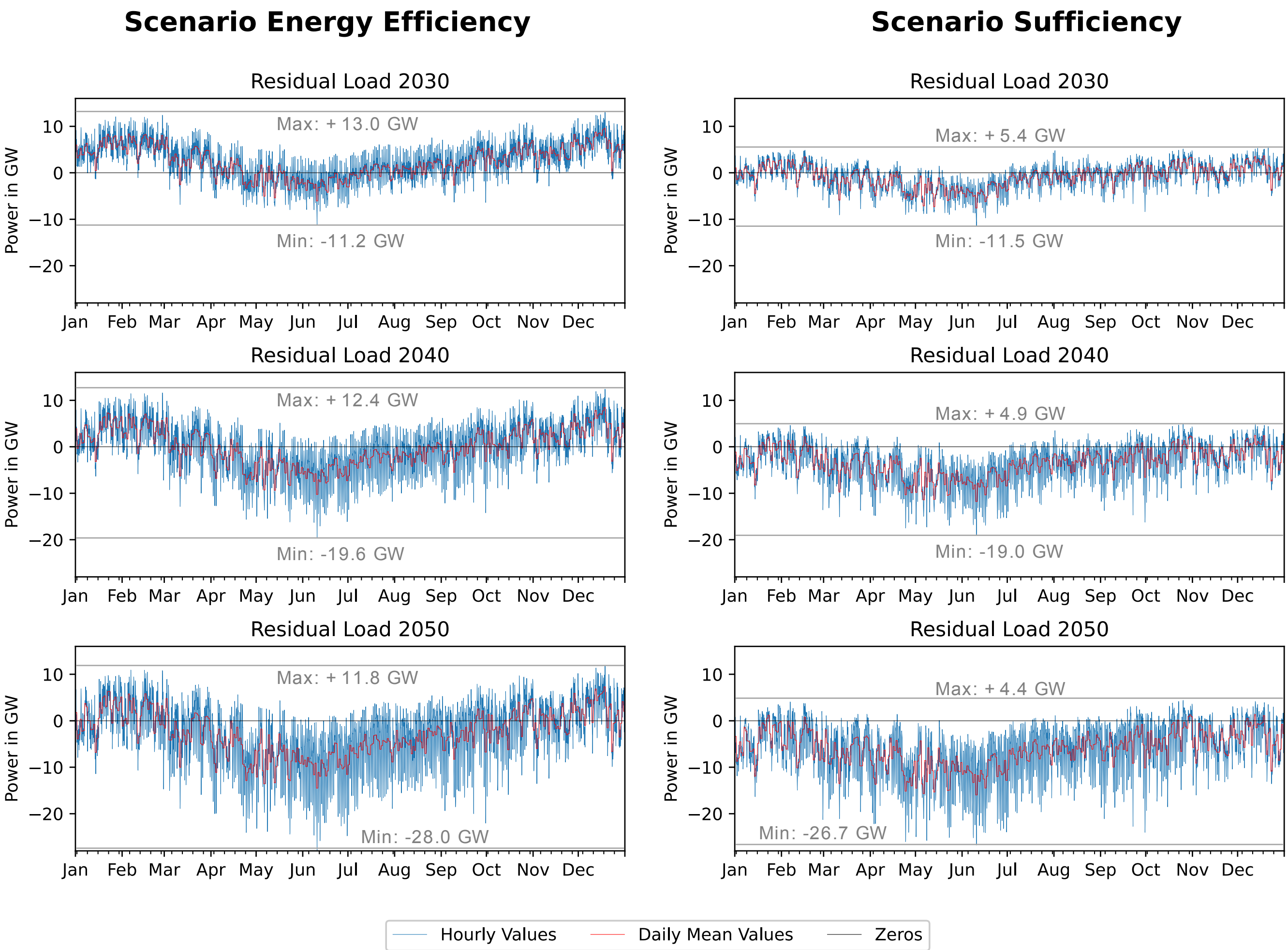

Figure 5. Residual load of both scenarios for all considered years.

Explanations of the difference in residual loads: This pattern has two causes. Firstly, there are differences between the two scenarios in the operation of electricity generation. While in the scenario *Energy Efficiency* only the fluctuating generation is not controllable, in the scenario *Sufficiency*, it is additionally the operation of industrial CHPs as well as waste and woody biomass fired CHPs (Section 2.1.3). In contrast, to maximize efficiency, all power plants can be operated flexibly in the scenario *Energy Efficiency* (2.1.2). Thus, the sufficiency scenario has a higher not controllable generation, especially in winter. Secondly, the scenario *Energy Efficiency* shows a significantly higher degree of electrification than the scenario *Sufficiency*, as well as more controllable electricity consumers. In the scenario *Sufficiency*, the storages, as well as the electrolysis are the only controllable electricity consumers (Section 2.1.3). In comparison, the scenario *Energy Efficiency* has additionally the central district heating grid supplying heat pumps, which can be operated flexible (Section 2.1.2). The combination of these two causes explains the differences in the resistive loads of the two scenarios.

Difference in residual loads available for electrolysis: As mentioned in the methodology, to determine the economically viable share of the negative residual loads that can be consumed by electrolysis, the complete ones as shown in Figure 5 are used as the basis. Beforehand, the residual loads are smoothed by controllable power generators and consumers such as pumped storage power plants. In addition to storages and flexible power plants (which are considered in both scenarios), flexible central heat pumps are also used exclusively in the scenario *Energy Efficiency* to supply the district heating system to maximise overall exergy efficiency. The accumulated negative residual loads available for electrolysis in the scenario *Energy Efficiency* for the years 2030, 2040 and 2050 amount to 1, 7 and 20 TWh_{el}/a, respectively. In the other scenario, they are significantly higher. For the scenario *Sufficiency*, the negative residual loads usable for electrolysis amount to 11, 30 and 53 TWh_{el}/a for the years 2030, 2040 and 2050, respectively.

Explanation of the difference in residual loads available for electrolysis: The difference can be explained by the larger negative residual load (mentioned before) and the fact that in the scenario *Sufficiency* there are no additional controllable central heat pumps as in the scenario *Energy Efficiency*. In the following subsection, the technical, as well as the economic national green hydrogen potential, is determined based on these negative residual loads.

3.2. Results of the Techno-Economic Analysis

Correlation of $LCOH_2$, full-load hours and plant size: In accordance with the methodology of the techno-economic analysis (Section 2.2), first, the $LCOH_2$ (depending on the full-load hours, the size of the plant and the considered year) were calculated. Small plants have a power range between 1 to 10 MW_{el}, medium plants between 10 to 50 MW_{el} and large plants between 50 and 100 MW_{el}. The results show the major influence of the full-load hours on the $LCOH_2$ (Table 4). Furthermore, it can be determined that larger plants have lower $LCOH_2$ than small ones and that the plants (independent of the size and full-load hours) will get cheaper over time based on the anticipated learning rates.

Table 4. $LCOH_2$ as a function of electrolysis size and number of full-load hours for the years 2030, 2040 and 2050. $LCOH_2$ is derived from cost structures represented in Table 2.

Full-Load Hours in h/a	$LCOH_2$ in €ct/kWh_{HHV}								
	Small Plants [A] 2030	Medium Plants [B] 2030	Large Plants [C] 2030	Small Plants [A] 2040	Medium Plants [B] 2040	Large Plants [C] 2040	Small Plants [A] 2050	Medium Plants [B] 2050	Large Plants [C] 2050
8000	7.1	6.8	6.7	5.0	4.8	4.7	3.9	3.8	3.7
7500	7.4	7.0	6.9	5.1	4.9	4.9	4.1	3.9	3.8
7000	7.6	7.3	7.1	5.3	5.1	5.0	4.2	4.1	4.0
6500	7.9	7.5	7.4	5.6	5.3	5.2	4.5	4.3	4.2
6000	8.2	7.8	7.7	5.8	5.6	5.5	4.7	4.5	4.4
5500	8.7	8.2	8.0	6.1	5.8	5.7	5.0	4.7	4.7
5000	9.1	8.6	8.4	6.5	6.2	6.1	5.3	5.1	5.0
4500	9.7	9.2	9.0	7.0	6.6	6.5	5.7	5.4	5.3
4000	10.5	9.8	9.6	7.5	7.1	7.0	6.2	5.9	5.8
3500	11.4	10.7	10.4	8.3	7.8	7.6	6.9	6.6	6.4
3000	12.6	11.8	11.5	9.3	8.7	8.5	7.8	7.4	7.2
2500	14.5	13.5	13.1	10.7	10.0	9.8	9.0	8.5	8.4
2000	17.4	16.1	15.6	12.7	11.9	11.6	10.9	10.3	10.0
1500	22.1	20.4	19.8	16.2	15.1	14.7	14.0	13.1	12.8
1000	31.6	29.0	28.1	23.1	21.5	20.9	20.2	18.9	18.4
500	60.0	54.8	52.9	43.8	40.6	39.4	38.7	36.1	35.2

[A] Small plants from 1 to 10 MW_{el}, Ø 5 MW_{el}; [B] medium plants between 10 and 50 MW_{el}, Ø 30 MW_{el}; [C] large plants between 50 and 100 MW_{el}, Ø 75 MW_{el}.

In Table 4, the text colour (green/red) indicates the maximum $LCOH_2$ as economic limits at 15 €ct/kWh_{HHV} (used in this work for hydrogen cost competitiveness). It can be seen that the required number of full-load hours to meet this economic limit decreases over time, as well as for larger plant sizes. Higher full-load hours reduce the proportional capital-related costs per produced unit of hydrogen most significantly. The cost advantage of large plants over smaller ones, as well as of later considered years over earlier ones, can be linked to the techno-economic assumptions (Table 2).

Economic minimum of full-load hours: With the help of the previous analysis, the minimum full-load hours required to meet the maximum $LCOH_2$ of 15 €ct/kWh_{HHV} could be determined. As a result, the minimum full-load hours required are 2200 h/a (in 2030), 2000 h/a (in 2040) and 1500 h/a (in 2050). These minimum full-load hours are the same for both scenarios. By combining these minimum full-load hours with the negative residual loads available for electrolysis, the total maximum electrolysis size (in GW_{el}) could be determined for each scenario and year.

Comparison of the economic electrolyser sizes: The scenario *Energy Efficiency* has an economic green hydrogen potential only in 2050, due to the required full-load hours. The associated total electrolysis size is 5.9 GW_{el}. In the other scenario, all considered years fulfil the anticipated threshold for the minimum full-load hours. The electrolysis size was determined with 2.1, 5.9 and 11.0 GW_{el} for the years 2030, 2040 and 2050, respectively. In Figure 6, the total negative residual loads available for electrolysis are shown in grey. The economically feasible share due to the limited electrolysis size is indicated in blue. For both scenarios and each considered year, the figure contains a time-resolved representation (in each case on the left) as well as an ordered duration curve of the negative residual load hours (in each case on the right). The minimum required full-load hours can be easily identified from the ordered duration curve.

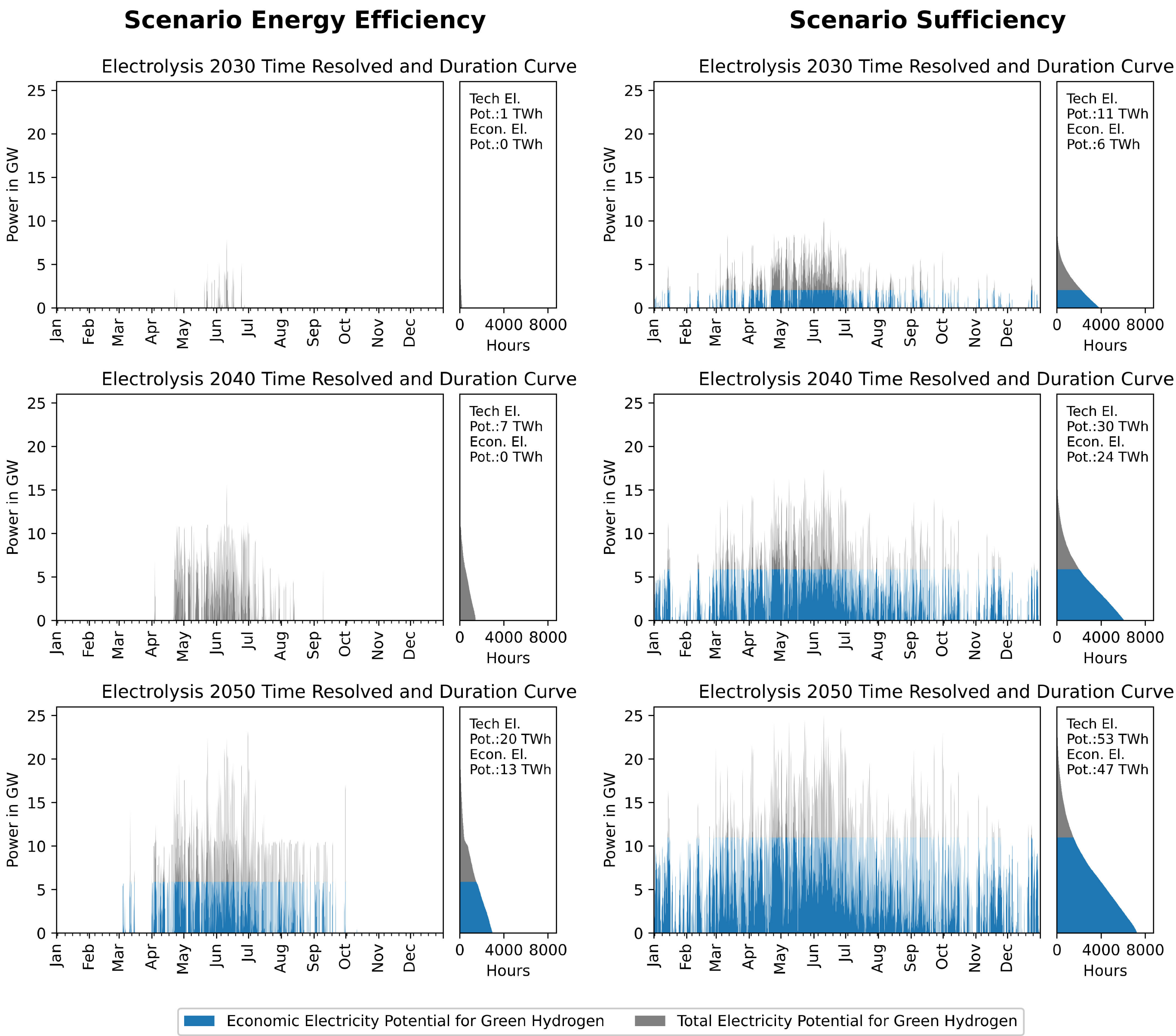

Figure 6. Technical potential of negative residual load usable by electrolysis (grey) as well as the economically realisable potential (blue). For each scenario and each considered year, the temporally resolved diagram (always left) and the ordered duration curve (always right) is shown.

Comparison and explanation of the technical and economic electricity potential for green hydrogen: The figure shows that the scenario *Energy Efficiency* has always a significantly lower total and economic potential for national green hydrogen, than the scenario *Sufficiency*. In the scenario *Energy Efficiency*, there is no economic potential until 2050. On the one hand, this is caused by the high degree of electrification and, on the other hand, it is the consequence of the availability of other controllable consumers such as heat pumps. Flexible operation during negative residual loads of central heat pumps can help increase overall efficiency [47].

Roll-out of electrolyser plants: Since the economic hydrogen production potential in the scenario *Energy Efficiency* is very low and only available in 2050, a more detailed roll-out and cost analysis will only be carried out for the scenario *Sufficiency* in the following. As mentioned in the methodology, the theoretical Austrian roll-out for electrolyser plants for the scenario *Sufficiency* was estimated based on a compound annual growth rate (CAGR) of 25% (Figure 7). Until 2030, mainly smaller plants in a capacity range between 0.5 and 1 MW_{el} will be installed. Subsequently, the expansion of medium-sized plants between 1 and 5 MW_{el} will also be accelerated. From 2030 onwards, it can also be assumed that more plants will be installed in a capacity range between 5 and 10 MW_{el}. Medium (10–50 MW_{el}) and large scale plants (50–100 MW_{el}) significantly contribute to the increase in capacity in the ramp-up curve in the second half of the considered period. In total, an installed capacity of more than 10 GW_{el}, represented in more than 500 plants till 2050, is anticipated in the developed roll-out scenario to reach a national green hydrogen production capacity. According to this roll-out scenario, a continuous capacity expansion would have to begin in 2021, and especially in the period 2040–2050; a doubling of already anticipated capacities and the number of plants is required to fully valorise the potential.

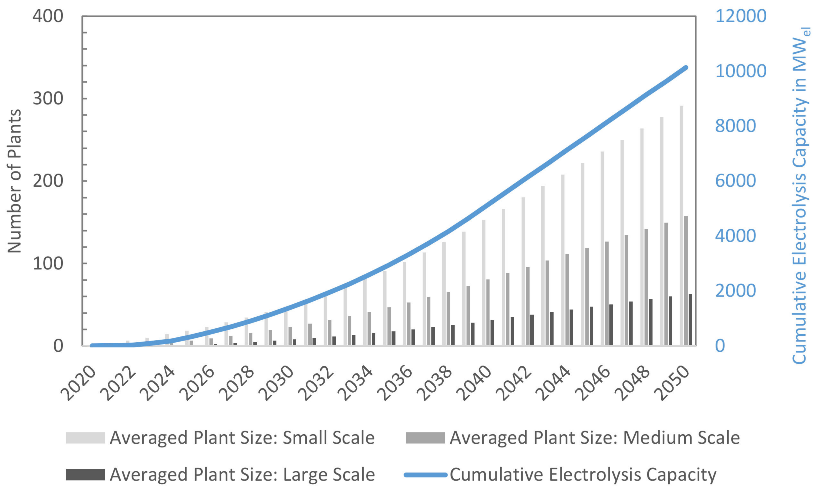

Figure 7. Roll-out curve of electrolyser plants in the scenario *Sufficiency*, considering economic boundary conditions 2021–2050.

The final cost structure of the $LCOH_2$: It is shown for the scenario *Sufficiency* in Figure 8. The figure represents the proportion of CAPEX and OPEX (orange and yellow shades) as well as revenues from the sale of by-products such as oxygen and excess heat (grey). The final costs resulting from all costs and proceeds are marked with a black line. All costs are averaged according to the actual hydrogen production. The final average levelised cost of hydrogen ranges between 12.1 (in 2030) and 6.3 €ct/kWh_{HHV} (in 2050). Electricity costs, as well as electricity grid tariffs and charges, account for the largest share of the costs. The figure shows a significant decrease in the resulting costs over time. This is mainly related to the electricity costs and the capital-related costs. According to the scenario assumption, the costs for electricity are decreasing (Section 2.2 and Table 2) based on the excess from a strong expansion of fluctuating renewables. The decrease of the capital-related costs is caused by learning curves (Table 2) as well as the significant increase in full-load hours over time, since only negative residual loads can be used.

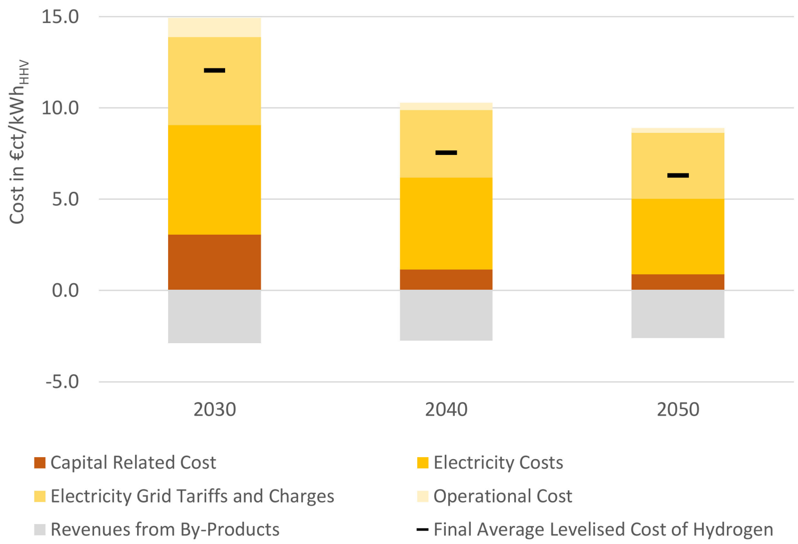

Figure 8. Averaged hydrogen production cost structure for scenario *Sufficiency.*

3.3. Import Demand of Renewable Gases

This subsection combines the results of Sections 3.1 and 3.2 to determine the import demand of renewable gases. Based on the total renewable gas consumption and the national renewable gas production, the import demand can be determined. In both scenarios, the national sustainable methane potential (from anaerobic digestion) is considered in addition to the technical and economic national green hydrogen potential. Furthermore, exclusively in the scenario *Energy Efficiency*, the technical potential of wood gas via the gasification of woody biomass is also included. Wood gasification and wood gas utilisation enable a better exergetic utilisation of woody biomass than the typical thermal biomass utilisation for the provision of low-temperature heat such as space heating [47]. In this section, first the technical import demand (use of all technical potentials) and then the economic import demand (use of exclusively economic production) are discussed.

Total consumption of renewable gases: The results show the total consumption is between 99 and 195 TWh/a, depending on the scenario and the considered year (Figure 9). About 8, 12 and 16 TWh_{SM}/a are provided by national sustainable methane production (both scenarios), depending on the considered year. Furthermore, a technical wood gas potential of about 28 TWh_{WG}/a is supplied by the gasification of woody biomass (only the scenario *Energy Efficiency*), independent of the considered year. When considering the technical potential, between 0.3 and 37.2 TWh_{H2}/a of green hydrogen can be produced by national electrolysis plants. The rest, between 41 (scenario *Energy Efficiency* 2050) and 180 TWh/a (scenario *Sufficiency* 2030) of renewable gases must be imported.

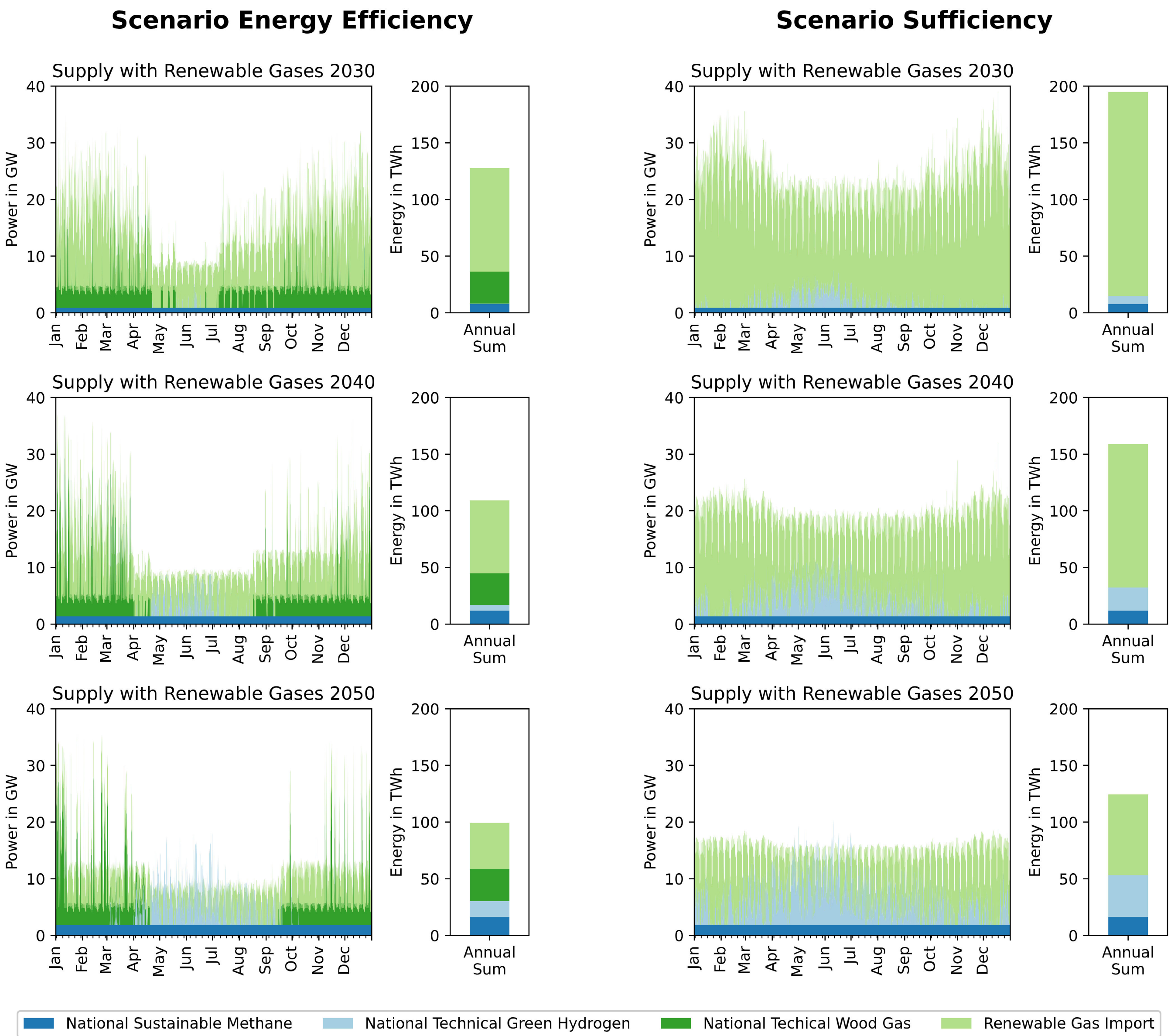

Figure 9. Sources of the required renewable gases. For each scenario and each considered year, the temporally resolved diagram and the annual sum of the technical potentials and import demand are shown.

Comparison of the technical supply with renewable gases: The time resolved and annual sum of the technical potentials and import demand is shown in Figure 9. The technical green hydrogen potential of the scenario *Energy Efficiency* is between 0.3 in 2030 and 14.1 TWh_{H2}/a in 2050. For comparison, in the scenario *Sufficiency*, it ranges between 7.1 TWh_{H2}/a in 2030 and 37.2 TWh_{H2}/a in 2050. Despite the higher technical green hydrogen production in the scenario *Sufficiency*, the gasification of woody biomass in the scenario *Energy Efficiency* leads in total to a larger share of renewable gas self-supply for each considered year, compared to the scenario *Sufficiency* (2030: 28 compared to 8%, 2040: 41 compared to 20%, 2050: 59 compared to 43%). A seasonal component can be identified in both scenarios, especially in 2030. However, this seasonal component significantly reduces over time. National green hydrogen is mainly produced in summer, while sustainable methane production does not show seasonal fluctuations. In the scenario *Exergy Efficiency*, wood gas production is volatile but primarily in winter.

Explanation of the difference in the technical gas supply: The lower hydrogen production in the scenario *Energy Efficiency* can be explained by the lower amount of negative residual loads available for electrolysis plants (Sections 3.1 and 3.2). The seasonality of gas consumption is caused by two effects: On the one hand, renewable gases are needed to generate electricity to compensate for the positive residual load in the winter half-year. On the other hand, there is a significantly higher demand for space heat in the winter half-year. In the scenario *Energy Efficiency*, the demand for space heating is almost exclusively covered by heat pumps. For this reason, significantly more electricity must be provided by CHPs in winter in this scenario. In contrast, in the scenario *Sufficiency*, part of the space heating is covered by the incineration of renewable gases. The expansion of renewables in 2040 and 2050 reduces the need for controllable generations to cover the positive residual load. In addition, the final energy consumption decreases over time in both scenarios. Accordingly, the demand for space heating and its seasonal component also decreases. This effect on reduction is significant in the scenario *Sufficiency* due to the strong assumptions of behavioural changes. Due to the easy storability of woody biomass as well as of wood gas, the gasification plant can be operated very flexibly when excess heat (at about 90 °C) is needed. Accordingly, wood gasification only operates if the excess heat can be used. Since these are technical analyses, this also explains the large power peaks of gasification in Figure 9. As a consequence, operations take place primarily in winter due to the greater heat demand. In contrast, the operation of electrolysis is primarily in summer, due to the negative residual loads. According to the assumptions, sustainable methane is produced constantly.

Comparison of technical and economic supply with renewable gases: The small amount of negative residual loads for hydrogen production results in economic green hydrogen potentials in the scenario *Energy Efficiency* only in the year 2050. Accordingly, as mentioned above, national economic green hydrogen potential is only analysed for the scenario *Sufficiency*. The direct comparison of the technical and economic potential of national green hydrogen shows that a reduction in national production must be compensated for by an increase in renewable imports (Figure 10). However, the difference between technical and economic green hydrogen potentials has little impact on total renewable gas imports (2030: +1.7%; 2040: +3.2%; 2050: +4.0%). The absolute difference is between 3 and 4 TWh/a for all considered years. The small difference shows that an evaluation of renewable gas imports based on technical potential provides a good estimate in comparison to a more detailed economic analysis.

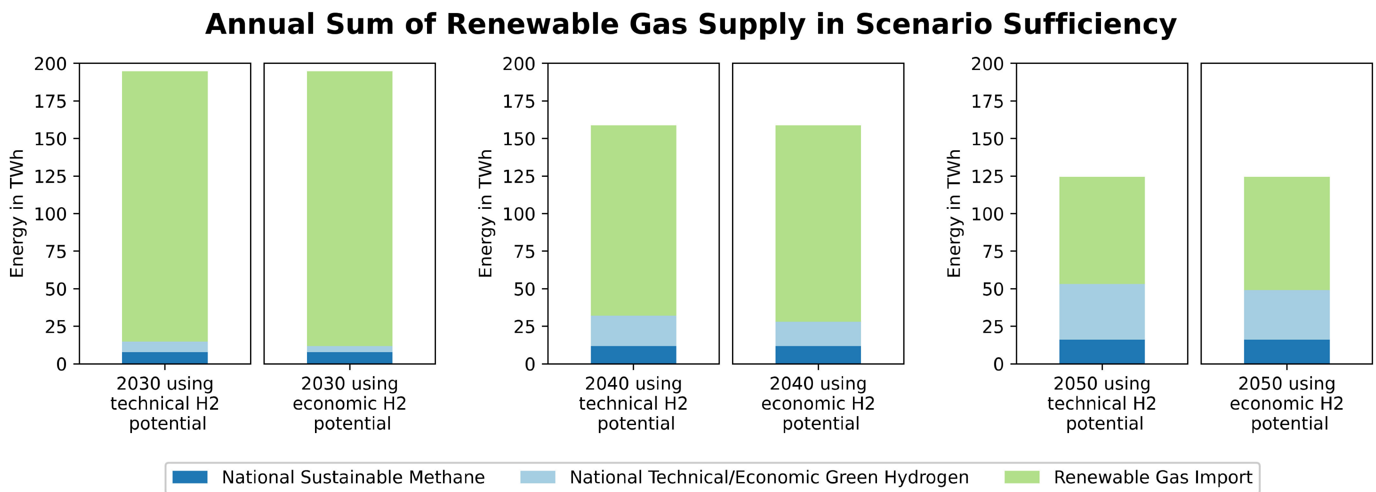

Figure 10. Comparison of renewable gas sources for the two cases: technical and economic green hydrogen potentials (only for the scenario *Sufficiency*).

3.4. Performance Indicators

Finally, this subsection presents performance indicators for both scenarios and the years 2030, 2040 and 2050 in Table 5. It represents a total overview of the results from Sections 3.1–3.3.

Table 5. Overview of the performance indicators for both scenarios and all considered years.

Performance Indicator	Scenario *Energy Efficiency* 2030	2040	2050	Scenario *Sufficiency* 2030	2040	2050
Primary energy consumption in TWh/a	236	232	233	320	285	252
Final energy consumption in TWh/a	231	227	206	259	225	194
Renewable energy generation and production in TWh/a	138	163	189	138	163	189
Total negative residual loads in TWhel/a	1	7	20	11	30	53
Lower limit for full-load hours of electrolyser plants in h/a [1]	2200	2000	1500	2200	2000	1500
Installed electrolysis capacity in GWel	0.0	0.0	5.9	2.1	5.9	11.0
Negative residual loads used for electrolysis in TWhel/a	0	0	13	6	24	47
Share of negative residual loads used for electrolysis in %	0	0	67	57	80	89
Technical green hydrogen production in TWhH2/a	0	5	14	7	20	37
Economic green hydrogen production in TWhH2/a	0	0	9	4	17	34
Total consumption of renewable gases in TWh/a	128	109	99	195	159	125
Required import of renewable gases (based on technical potentials) in TWh/a	91	64	41	180	127	71
Required import of renewable gases (based on economic potentials) in TWh/a	- [3]	- [3]	- [3]	183	131	76
Share of technical national renewable gas production in %	28 [2]	41 [2]	59 [2]	8	20	43
Averaged levelised cost of national produced green hydrogen in €ct/kWhHHV	- [3]	- [3]	- [3]	12.1	7.5	6.3
Minimal levelised cost of national produced green hydrogen in €ct/kWhHHV	- [3]	- [3]	- [3]	9.6	5.0	3.7
Maximal levelised cost of national produced green hydrogen in €ct/kWhHHV	- [3]	- [3]	- [3]	14.5	12.7	13.9

[1] Maximal $LCOH_2$ economic limit of 15 €ct/kWh_{HHV}; [2] including national wood gas production; [3] not calculated due to the small potential of the scenario, as mentioned in Section 3.2.

4. Discussion

This section first analyses the relations between economic green hydrogen potential, the averaged $LCOH_2$ and the maximum $LCOH_2$ economic limit (Section 4.1). Then, in Section 4.2, the resulting averaged $LCOH_2$ of national green hydrogen production determined in this study are compared with the costs documented in other publications.

4.1. Techno-Economic Relations

For the analysis, the negative residual load that can be used for green hydrogen production and their cost structures are investigated. This analysis was performed for the scenario *Sufficiency* only. To compare the economic green hydrogen potential and the resulting average $LCOH_2$, no minimum full-load hours or maximum $LCOH_2$ economic limits were taken into account. Instead, these two values were calculated in increments of 500 full-load hours over the entire available time range of the ordered duration curve for all considered years. The time range of the ordered duration curve starts for all considered years with 0 full-load hours (i.e., the maximum negative residual load peak power) and ends as soon as the negative residual load power drops to 0 (see duration curve in Figure 6).

The average $LCOH_2$ for a certain hydrogen potential is calculated by the actual potential weighted mean of all $LCOH_2$ of the individual 500 full-load hour increments, which are necessary to reach the potential. The comparison of the averaged $LCOH_2$ and the corresponding economic green hydrogen potentials for all three considered years is shown in Figure 11. In addition, this figure also shows different maximum $LCOH_2$ economic limits and their effect on averaged $LCOH_2$ as well as on the reachable green hydrogen potential. The maximal $LCOH_2$ economic limit of 15 €ct/kWh_{HHV} (applied in this work) is indicated in red.

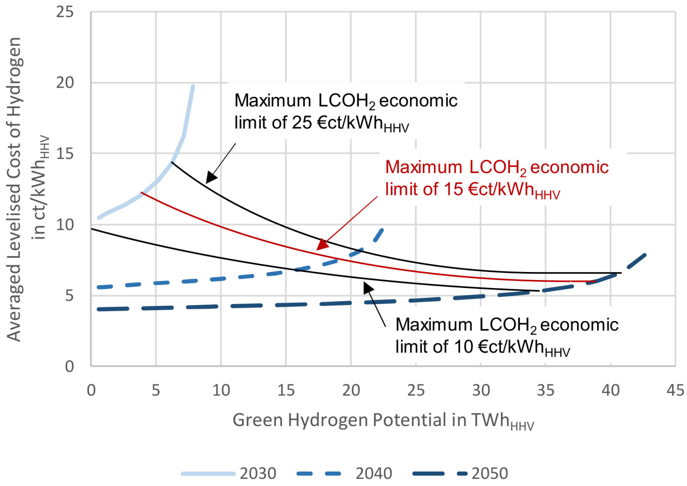

Figure 11. Relation between averaged levelised cost of hydrogen and economic green hydrogen potential. In addition, the maximum $LCOH_2$ economic limits (corresponding to the full-load hours) are visualised for 10, 15 and 25 €ct/kWh_{HHV}.

Figure 11 shows that greater potential utilisation leads to higher average $LCOH_2$. The slope of the curves is small at low potential utilisation and becomes increasingly larger towards maximum potential utilisation. Thereby, the slope increases by a factor between 10 (2030) and 32 (2050). Thus, the utilisation of the last few per cent of the potential leads to a significant increase in average $LCOH_2$. The curve for the year 2050 shows a significantly lower slope at the maximum potential than the other curves. This is primarily caused by the averaging of the $LCOH_2$. The higher the potentials with low $LCOH_2$ (high number of full-load hours), the smaller the effect of small potentials with high $LCOH_2$ (low number of full-load hours). The maximum available full-load hours based on the negative residual load available for electrolysis in 2030, 2040 and 2050 are 3855, 6097 and 7267 h/a, respectively.

A comparison of the curves shows that the averaged $LCOH_2$ in 2050 are significantly lower than in 2040 or 2030. This can be explained by two aspects: On the one hand, CAPEX and electricity costs will decrease according to the anticipated learning effects (Table 2). On the other hand, according to the scenario assumptions, there will be significantly higher full-load hours in 2050 (due to the higher renewable generation and decreasing demand), which will lead to significantly lower specific costs and higher economic green hydrogen potential.

In 2030, increasing the maximum $LCOH_2$ economic limit from 15 €ct/kWh_{HHV} to 25 €ct/kWh_{HHV} has a significant impact on the average $LCOH_2$ as well as the potential (Figure 11): +2.3 TWh_{HHV} (+57%) of potential but averaged $LCOH_2$ would increase by 2.2 €ct/kWh_{HHV} (+18%). For comparison, in 2050 the same change in maximum $LCOH_2$ economic limit only leads to a change of +0.6 €ct/kWh_{HHV} (+9%) on the average $LCOH_2$ as well as a change in the potential increase of 1.9 TWh_{HHV} (+5%). Therefore, the relative impact in 2030 is significantly higher than in 2050. This can be explained by the large difference in the total potential with a maximum $LCOH_2$ economic limit of 15 €ct/kWh_{HHV} for these two considered years (2030: 4.0 TWh_{HHV}; 2050: 39.0 TWh_{HHV}), while the increase in potential due to a higher maximum $LCOH_2$ economic limit is comparable (2.3 TWh_{HHV} for 2030, 1.9 TWh_{HHV} for 2030) as well as by the averaging of the $LCOH_2$; a high share of the potential with low costs can nearly compensate a small share of the potential with higher costs, due to the method of actual potential weighted averaging.

4.2. Overview of Hydrogen Production Cost Trend in the Literature

In this subsection, the hydrogen production costs available in the literature are compared with the costs determined in this work. A distinction is made between the resulting costs of green, blue and grey hydrogen.

The Energy Transition Commission [64] clearly states that blue hydrogen will always be more expensive than grey hydrogen, as long as there is no carbon price. They also point out that in the medium term, green hydrogen may be cheaper than grey hydrogen in many regions because of a fall in prices for renewable energy and electrolysers. However, CO_2 emission prices are important to make clean hydrogen types competitive with fossil fuels. The Hydrogen Council [65] states that green hydrogen will become cost-competitive in the future because of three aspects: the levelised costs of energy are declining, a significant decrease in electrolyser CAPEX can be expected and the full-load hours continue to increase. With the introduction of carbon costs, green hydrogen could be cost-competitive around 2030 [65]. According to the International Energy Agency's (IEA) [66] prognosis, a cost reduction of up to 30% by 2030 is possible for the production of green hydrogen because of declining costs of renewables. IRENA says that in the best locations, renewable hydrogen will be competitive with hydrogen derived from fossil fuels within 3–5 years, and they also point out that CO_2 prices are beneficial for green hydrogen to become competitive [67].

Table 6 compares the costs of different types of hydrogen production over time, published in the literature. The costs of grey, blue and green hydrogen (including CO_2 emission costs) are visualized in Figure 12. It can be seen how the costs for green hydrogen are decreasing. The costs for grey hydrogen are rising due to the CO_2 emission costs. The costs determined in this study for the production of green hydrogen from negative residual loads in Austria amount to 12.1, 7.5 and 6.3 €ct/kWh_{HHV} in 2030, 2040 and 2050, respectively (all values for the scenario *Sufficiency*). The comparison shows that the costs are in a comparable order of magnitude, but due to the low full-load hours (especially in 2030), they are not competitive with other concepts/regions with higher full-load hours (e.g., offshore wind generation or photovoltaics in desert regions exclusively for hydrogen production). However, if the national costs are compared with the import costs of green hydrogen (including transport costs), it becomes clear that the national costs are competitive (Table 6). In this context, it is important to note that the actual import costs in the future are still very uncertain. It is currently unclear whether hydrogen will be imported directly (compressed or liquefied) or chemically bound (e.g., as ammonia or methane). The costs for direct import in the 2030–2035 range from about 2.1 €ct/kWh_{HHV} (pipeline from Iberia) to 5.9 €ct/kWh_{HHV} (ship from Australia) [68]. The transport costs depend significantly on the transport distance. Hydrogen imported liquefied via ship from Morocco to Belgium is estimated at 3.3 €ct/kWh_{HHV} (in 2030–2035) [68]. For comparison, the Hydrogen Council expects 3.1 €ct/kWh_{HHV} for the ship transport of liquid hydrogen from Saudi Arabia to Germany in 2030 [60]. The high direct hydrogen transportation costs result from the required effort for liquefaction and refrigerated transport, as well as from the low volumetric energy density and thus higher costs per transported unit [68]. In the case of indirect hydrogen imports, the transport costs are significantly reduced, but additional costs arise for the conversion. According to the Hydrogen Roadmap Europe [69], various modes of transport for hydrogen are possible, as all of them are cheaper than a transmission grid for electricity.

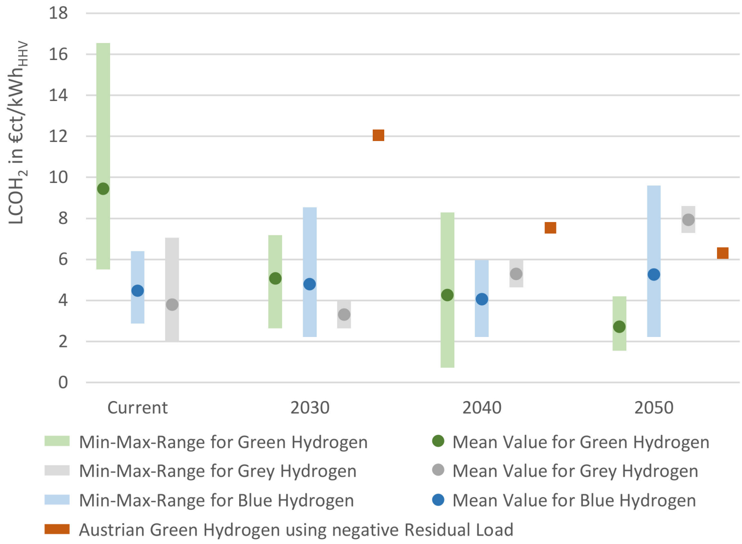

Figure 12. Literature overview of the development of hydrogen production costs over time. Green, blue and grey bars represent green, blue and grey hydrogen, respectively. All bars show the range in the literature between the minimum and maximum values. The dots represent the arithmetic mean. Blue and grey hydrogen include CO_2 emission costs. All values and corresponding sources can be found in Table 6. For comparison, the Austrian averaged $LCOH_2$ (determined in this study) are indicated by red squares.

In the future, the import of renewable gases will be important, since Austria cannot completely self-supply its demand for renewable gases (Section 3.3). For other European countries like Germany or Belgium, the situation is quite similar [24,68]. A problem in central European countries like Germany or Austria is the competition between renewable energy generation and other land use forms, which is not the case in unsettled areas in, for example, Northern Africa [24]. Therefore, renewable gas imports, mostly originating from solar energy in desert areas or wind energy from offshore wind plants seem to be the key strategy to satisfy the demand. However, this requires the implementation of new infrastructure. The Hydrogen Import Coalition [68] identifies regions like Morocco, Spain, Chile, Oman and Australia as promising.

As the import of green hydrogen will be a key aspect in the future, it is important to mention that the conditions in the export countries must also be taken into account, so that no disadvantages arise regionally for people and the environment. Accordingly, support for the global south is necessary, as the energy demand in urban environments in these regions is rising. In addition to the advantages of importing, it is nevertheless important to consider the dependence of the energy supply on exporting countries [24].

Table 6. Production price comparison for different hydrogen types until 2050.

Type	Hydrogen Price (€ct/kWh$_{HHV}$)			
	Current	2030	2040	2050
Production of Grey	*Including CO_2 emission costs*			
	2.4–3.8 [3] 2.0–7.1 [4]	2.6–4.0 [3]	4.6–6.0 [3]	7.3–8.6 [3]
	Excluding CO_2 emission costs			
	4.0 [1] 1.8–3.1 [3] 1.5–4.9 [7] 3.8 [8]	1.8–3.1 [3]	1.8–3.1 [3]	1.8–3.1 [3]
Production of Blue	*Including CO_2 emission costs*			
	3.3–6.4 [4] 2.9–5.5 [6]	5.0 [1] 2.2–3.5 [3] 2.9–5.7 [6] 5.5–8.5 [10]	4.8 [1] 2.2–3.5 [3] 3.1–6.0 [6]	2.2–3.5 [3] 3.3–6.4 [6] 6.6–9.6 [10]
	Excluding CO_2 emission costs			
	4.9 [1] 3.1–7.5 [5] 2.9–6.4 [7] 5.1 [8]	3.0–7.5 [5]		3.0–6.6 [5]
Production of Green	8.0 [1] 8.8–12.1 [3] 6.6–16.6 [4] 5.5–10.2 [5] 5.7–14.8 [6] 5.7–9.9 [7] 6.3–14.0 [8]	6.0 [1] 2.9–5.1 [3] 2.6–6.0 [5] 3.5–7.1 [6] 4.4–7.2 [10]	5.2 [1] 2.2–4.2 [3] 2.6–5.5 [6] 0.7–8.3 [10]	1.8–3.3 [3] 1.6–3.5 [5] 2.0–4.2 [6]
Production and Import of Green (incl. transport cost)	25.0–27.5 [2]	16.0–22.0 [2] 6.5–9.0 [9] 7.5 [11]	14.0–17.5 [2]	12.0–13.0 [2] 5.5–7.5 [9]

Assumptions for conversion: 1 € = 1.15 USD; HHV of H_2: 39.4 kWh/kg. [1] [70], CO_2 price: unknown but included. [2] [34], considers import to Germany. [3] [65], CO_2 prices: 26.09 €/t_{CO2} (2020), 43.48 €/t_{CO2} (2030), 130.43 €/t_{CO2} (2040), 260.87 €/t_{CO2} (2050). [4] [66], CO_2 prices [71]: 0–18.4 €/t_{CO2} (2020), 86.3–115.0 €/t_{CO2} (2030), 166.8–184.0 €/t_{CO2} (2050). [5] [72], no carbon tax applied. [6] [67], CO_2 prices: 43.48 €/t_{CO2} (2030), 86.96 €/t_{CO2} (2040), 173.91 €/t_{CO2} (2050), depicted max. values are avg. values (actual max. values not available for public purposes). [7] [64], no carbon tax applied. [8] [73], no carbon tax applied. [9] [68], considers import to Belgium. [10] [74], CO_2 prices: 100 €/t_{CO2} (2030), 150 €/t_{CO2} (2040). [11] [60], export from Saudi Arabia to Germany.

5. Conclusions

By combining the results with the discussion, the following main conclusions can be drawn:

Renewable gases will be crucial in the future to reach our climate targets: Depending on the scenario and the considered year, renewable gas consumption between 99 and 195 TWh/a was identified. For comparison, Austria had a total natural gas consumption of about 89 TWh/a in 2019 [38].

Massive expansion of renewables is mandatory for national green hydrogen production. Nevertheless, the share is small compared to the import demand. In this paper, only negative residual loads from renewable sources are used for the production of green hydrogen. To reach significant negative residual loads, massive expansion of renewables is required. In the scenarios, the already ambitious renewable expansion plan until 2030 [29] was extrapolated linearly until 2050. Despite this massive expansion, the maximum technical green hydrogen potential can only cover about 14 and 30% of the total renewable gas consumption for the scenarios *Energy Efficiency* and *Sufficiency* in 2050, respectively. Based on the maximum potential of sustainable methane from biogenic sources in Austria [52], at least 54% of the renewable gas consumption must be imported. Considering the assumptions used in this study, the minimum import share is even higher (57%).

Higher $LCOH_2$ can be accepted at the beginning if the expansion of renewables is continued: An increasing number of full-load hours of the electrolysis (due to expansion of renewables) leads to decreasing averaged $LCOH_2$. Lower full-load hours are expected at the beginning of the electrolysis plant roll-out. Accordingly, the maximum $LCOH_2$ economic limit can be set higher at the beginning. When a high number of full-load hours is reached, the higher maximum $LCOH_2$ economic limit does not lead to a significantly higher average $LCOH_2$. The cost analysis has also shown that the use of all available negative residual loads increases the average costs due to the low number of full-load hours for the last few per cent of additional hydrogen production. Accordingly, a maximum $LCOH_2$ economic limit is suggested if no further significant increase in negative residual loads is to be expected. It ensures that no excessive increase in the average $LCOH_2$ is to be anticipated. To reduce costs, in the beginning, a non-exclusive supply with negative residual loads can be applied. Supply from the grid can increase full-load hours but will also lead to higher electricity costs.

The costs of nationally produced green hydrogen are comparable to the costs of importing green hydrogen: The comparison of the resulting averaged levelised cost of hydrogen with other studies shows that the national green hydrogen production is more expensive, especially in 2030. This is mainly caused by the low number of full-load hours reachable based on the scenarios to exclusive utilise negative residual loads. In 2040 and 2050, the available negative residual loads, as well as the full-load hours, are significantly higher than in 2030. Consequently, the average cost decreases. National green hydrogen is becoming competitive, especially in comparison with imported green hydrogen (including transport costs).

In this paper, two fully decarbonised scenarios are considered. Accordingly, there are no energy-related CO_2 emissions in Austria. However, the actual reduction of CO_2 emissions through the measures discussed in this study is not quantifiable. It depends on the actual sources of the imported gases. As mentioned in the introduction, hydrogen can be produced using different processes (grey, blue, turquoise, pink or green hydrogen). Each of these processes can be attributed to different amounts of CO_2 emissions per quantity of hydrogen produced (carbon footprint). Accordingly, it is a global task to ensure the use of exclusively renewable sources for the provision of renewable gas. Only this can ensure the full decarbonisation of countries with energy import demands.

The results clearly indicate the strong demand for cheap renewable electricity production as a prerequisite for the upscale and broad roll-out of electrolysis technologies. Accordingly, very rapid expansion of renewables but also of electrolysis plants are required, nationally and internationally to reach the goal of climate neutrality.

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Nomenclature of abbreviations

A	Annuity of total annual payments
A_C	Annuities of capital-related costs
A_D	Annuities of demand-related costs
A_O	Annuities of operation-related costs
A_P	Annuity of proceeds from by-product sales
A_M	Annuities of other costs
C_{var}	Demand related variable costs
CAGR	Compound annual growth rate
CAPEX	Capital expenditures, investment cost
CCS	Carbon capture and storage
CHP	Combined heat and power plant
CO_2	Carbon dioxide
EAA	Environmental Agency Austria
EU	European Union
$Ex_{LossDest,tot}$	Total of exergy losses and exergy destruction, caused by both energy conversion, transportation and distribution systems as well as final energy applications
$Ex_{Sup,tot}$	Total exergy used for supplying the national energy system
$Ex_{UED,tot}$	Total useful exergy demand of all national energy services
$Ex_{NatGP,i}$	National renewable generation or production of resource i
$Ex_{Imp,j}$	Exergy import of energy carrier j
$Ex_{Exp,k}$	Exergy export of energy carrier k
f	Objective function
GW_{el}	Gigawatt of electrical power
h	Hours
H_2	Hydrogen
HHV	Higher heating value
ICE	Internal combustion engines
kW_{el}	Kilowatt of electrical power
kWh_{H2}	Kilowatt hour of hydrogen based on LHV
kWh_{HHV}	Kilowatt hour of hydrogen based on HHV
LCOE	Levelised cost of electricity
$LCOH_2$	Levelised cost of hydrogen
LHV	Lower Heating Value
m^3H_2O	Cubic meter water
MW_{el}	Megawatt of electrical power
MWh_{el}	Megawatt hour of electrical energy
MWh_{th}	Megawatt hour of thermal energy
OPEX	Operational expenditures
p.a.	Per anno
$P_{H2,y}$	Annual hydrogen production
PV	Photovoltaic
t_{O2}	Tons of oxygen
t_{CO2}	Tons of carbon dioxide
TWh	Terawatt hour (independent of the type of energy)
TWh_{el}	Terawatt hour of electrical energy
TWh_{H2}	Terawatt hour of hydrogen based on LHV
TWh_{HHV}	Terawatt hour of hydrogen based on HHV
TWh_{SM}	Terawatt hour of sustainable methane
TWh_{WG}	Terawatt hour of wood gas
USD	United States Dollar
WAMplus	With Additional Measures Plus
€	Euro
€ct	Eurocent
/a	Per annum

Appendix A

Appendix A.1 Additional Information of Scenario Energy Efficiency

Table A1 summarises the exergy demands taken into account in the scenario *Energy Efficiency* to cover all Austrian energy services. Table A2 to Table A8 provide a complete list of available conversion technologies, including the exergy efficiencies used. Maximum power is not limited. Available storage units can be found in Table A9. The exergy efficiencies considered here take into account both exergy destruction and exergy losses. Further details about all efficiencies can be found in [47].

Table A1. Useful exergy demand for the scenario *Energy Efficiency* (calculation based on [25]).

Type	Exergy Demand 2030 in TWh/a	Exergy Demand 2040 in TWh/a	Exergy Demand 2050 in TWh/a	Used Profile
Transport Demand Cars and Trucks	29.9	29.6	29.3	Cars [75,76] [2]; Trucks [77–79] [2]
Transport Demand Others	5.1	5.1	5.0	Aviation: Austrian Transport Report 2017 [80]; navigation: assumed as constant between 5 and 22 o'clock on working days and constant between 5 and 15 o'clock on Saturdays; railways: measured values of Austrian Railways [81]; pipelines: assumed as constant
Heat Demand (up to 100 °C)	19.0	18.9	18.7	FfE SigLinDe [82], combined industrial load profile [83] [1], synthetic load profiles [84] [1]
Heat Demand (100 to 400 °C)	11.7	11.6	11.5	Combined industrial load profile [83] [1], synthetic load profiles [84] [1]
Heat Demand (above 400 °C)	15.3	15.2	15.1	Combined industrial load profile [83]
Industrial Processes (Iron- and Steelmaking, Electrochemical Demand, Non-Energy Use)	29.1	28.8	28.5	Iron- and steelmaking assumed as constant; rest: combined industrial load profile [83] [1]
Stationary Engine Demand	16.3	16.1	15.9	Combined industrial load profile [83] [1], synthetic load profiles [84] [1]
Lighting and ICT Demand	4.3	4.3	4.2	Combined industrial load profile [83], synthetic load profiles [84]

[1] Without seasonal component; [2] outside temperature additionally taken into account for heating/cooling demand.

Table A2. Available CHPs of the scenario *Energy Efficiency* [47].

Type	Exergy Efficiency of Electricity	Exergy Efficiency of Usable Excess Heat	Exergy Destruction	Exergy Losses
Woody biomass fired CHP (Clausius–Rankine-cycle)	0.270	0.130	0.566	0.034
Wood gas fired CHP (ICE)	0.300	0.124	0.543	0.034
Fuel cell CHP (PEM)	0.639–0.659 [85]	0.064–0.065	0.310	0.045
Sustainable methane fired CHP (combined cycle)	0.590–0.630 [85]	0.049–0.058	0.310	0.034

Table A3. Available conversion units of the scenario *Energy Efficiency* [47].

Type	Exergy Efficiency of Conversion	Exergy Efficiency of Usable Excess Heat	Exergy Destruction	Exergy Losses
Water Electrolysis (PEM)	0.651–0.702 [85]	0.033–0.045	0.233	0.034
Methanation of Hydrogen to Sustainable Methane	0.800	0.011	0.155	0.034
Gasification of Woody Biomass to Wood Gas plus Methanation to Sustainable Methane	0.560	0.065	0.341	0.034
Gasification of Woody Biomass to Wood Gas	0.700	0.034	0.233	0.034
Production of Kerosene or Diesel from Hydrogen via Fischer–Tropsch-Synthesis	0.769	-	0.185	0.046
Production of Kerosene or Diesel from Sustainable Methane via Reforming and Fischer–Tropsch-Synthesis	0.650	-	0.281	0.069

Table A4. Available grids of scenario *Energy Efficiency* [47].

Type	Exergy Efficiency of Transport	Exergy Destruction	Exergy Losses
Electricity Grid	0.953	0.038	0.009
District Heating Grid (92 to 90 °C; return at 30 °C)	0.949	0.050	0.000
District Heating Grid (85 to 80 °C; return at 31 °C)	0.859	0.140	0.001
District Heating Grid (34 to 32.5 °C; return at 15 °C)	0.868	0.132	0.001
District Heating Grid (31 to 27.5 °C; return at 15 °C)	0.659	0.340	0.002

Table A5. Available conversion units for covering heat demand of the scenario *Energy Efficiency* [47].

Type	Overall Exergy Efficiency	Overall Exergy Destruction	Overall Exergy Losses
District Heating Application at 25 °C	0.254	0.746	0.000
District Heating Application at 65 °C	0.821	0.179	0.000
District Heating Application at 25 °C	0.864	0.136	0.000
Heat Pump (31 to 90 °C)	0.593	0.407	0.000
Heat Pump (80 to 100 °C)	0.849	0.151	0.000
Heat Pump (80 to 150 °C)	0.714	0.286	0.000
Heat Pump (between ambient and from 25 up to 150 °C)	0.500	0.500	0.000
Heat Supply at 25 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.0428	0.9076	0.0496
Heat Supply at 65 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.1383	0.8120	0.0496
Heat Supply at 100 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.2051	0.7453	0.0496
Heat Supply at 150 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.2813	0.6690	0.0496
Heat Supply at 250 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas, Woody Biomass) or Electric Direct Heating	0.3901	0.5497	0.0603
Heat Supply at 400 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas) or Electric Direct Heating	0.4926	0.4472	0.0603

Table A5. *Cont.*

Type	Overall Exergy Efficiency	Overall Exergy Destruction	Overall Exergy Losses
Heat Supply at 750 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas) or Electric Direct Heating	0.6149	0.3249	0.0603
Heat Supply at 1500 °C by Incineration of Chemical Energy (Hydrogen, Sustainable Methane, Wood Gas) or Electric Direct Heating	0.7143	0.2098	0.0759

Table A6. Available conversion units for covering transport demand of the scenario *Energy Efficiency* [47].

Type	Overall Exergy Efficiency for Movement	Overall Exergy Destruction	Overall Exergy Losses
BEV—Cars and Light Duty Trucks	0.741	0.229	0.030
BEV—Heavy Duty Trucks	0.734	0.236	0.030
Electric Locomotives	0.871	0.111	0.018
FC—Locomotives	0.491	0.406	0.103
FC—Cars and Light Duty Trucks	0.434	0.451	0.115
FC—Heavy Duty Truck (long-distances)	0.484	0.413	0.103
FC—Ship	0.276	0.621	0.103
Airplanes	0.276	0.225	0.499
ICE—Cars and Light Duty Trucks	0.268	0.459	0.274
ICE—Heavy Duty Truck	0.291	0.446	0.263
ICE—Ship	0.168	0.569	0.263
ICE—Locomotive	0.299	0.438	0.263

Table A7. Available conversion units for covering other demands of the scenario *Energy Efficiency* [47].

Type	Overall Exergy Efficiency	Overall Exergy Destruction	Overall Exergy Losses
LED Light	0.131 [86]	0.76	0.11
Electric Compressor for Gas Pipelines	0.840	0.16	0.00
Variable-Frequency Drive (Electric Engine)	0.880	0.08	0.04

Table A8. Available conversion units for covering both, heat and shaft work demand of the scenario *Energy Efficiency* [47].

Type	Exergy Efficiency of Provision of Shaft Work	Exergy Efficiency of Usable Excess Heat	Overall Exergy Destruction	Overall Exergy Losses
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 25 °C	0.500	0.018	0.422	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 65 °C	0.500	0.057	0.383	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 100 °C	0.500	0.084	0.355	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 150 °C	0.500	0.116	0.324	0.060
Methane fired Stationary Engine (ICE) with direct Excess Heat Usage at 250 °C	0.500	0.161	0.279	0.060

Table A8. *Cont.*

Type	Exergy Efficiency of Provision of Shaft Work	Exergy Efficiency of Usable Excess Heat	Overall Exergy Destruction	Overall Exergy Losses
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 25 °C	0.300	0.028	0.612	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 65 °C	0.300	0.089	0.550	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 80 °C	0.300	0.109	0.531	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 100 °C	0.300	0.133	0.507	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 150 °C	0.300	0.182	0.458	0.060
Wood Gas fired Stationary Engine (ICE) with direct Excess Heat Usage at 250 °C	0.300	0.252	0.387	0.060

Table A9. Parameter of the used storages in the scenario *Energy Efficiency*.

Type	Capacity in GWh_{el}	Max. Charging Power in GW_{el}	Max. Discharging Power in GW_{el}	Cycle Exergy Efficiency	Exergy Losses and Destruction over Time
Thermal Storage (low temperature)	unlimited [1]	unlimited [1]	unlimited [1]	0.951	3%/day
Thermal Storage (low medium)	unlimited [1]	unlimited [1]	unlimited [1]	0.938	5%/day
Waste Storage, Woody Biomass Storage	unlimited [1]	unlimited [1]	unlimited [1]	1	0 [2]
Wood Gas Storage, Sustainable Methane Storage, Kerosene Storage, Gasoline/Diesel Stroage	unlimited [1]	unlimited [1]	unlimited [1]	0.98	0 [2]
Hydrogen Storage	unlimited [1]	unlimited [1]	unlimited [1]	0.95	0 [2]
Battery Storages	2.1–11.8 [3,4]	1.1–5.9 [4,5]	1.1–5.9 [4,5]	0.9	0 [6]
Pumped Storages	160 [37]	1.2–3.6 [4,7]	1.4–4.3 [4,7]	0.8	0 [6]

[1] Storage for the district heating system and for chemical energy are not restricted in design for the purpose of maximum exergy efficiency [47]. [2] Losses over time for chemical storages are neglected. [3] Capacity calculated based on [87] corresponding to the photovoltaic rooftop expansion. Photovoltaic rooftop is about 40% of total photovoltaic potential (Table 1) [25]. [4] Range covers the different considered years between 2030 (min value) and 2050 (max value). [5] Typical ratio between capacity and power for commercial and industrial photovoltaic storages is chosen [88]. [6] Due to the short storage period, the losses over time are neglected. [7] Power is increased over time until maximum expansion [37] is reached.

Appendix A.2 Additional Information of Scenario Sufficiency

Tables A10 and A11 show the used data for final energy consumption and the energy consumption of the energy supply system, including the load profiles. The data are based on the WAMplus scenario of the Environment Agency Austria [40] but has been modified to ensure full decarbonisation. The parameter of storages, the efficiencies of the conversion units as well as the specific consumption of land transport are shown in Tables A12–A14.

Table A10. Final energy consumption for the scenario *Sufficiency* final energy (calculation based on [40]).

Type	Energy Consumption 2030 in TWh/a	Energy Consumption 2040 in TWh/a	Energy Consumption 2050 in TWh/a	Used Profile
Transport Cars and Trucks	58.7	48.1	36.7	Cars [75,76] [2]; Trucks [77–79] [2]
Transport Others	14.8	15.6	15.8	Aviation: Austrian Transport Report 2017 [80]; navigation: assumed as constant between 5 and 22 o'clock on working days and constant between 5 and 15 o'clock on Saturdays; railways: measured values of Austrian Railways [81]; pipelines: assumed as constant
Residential Sector	56.2	46.4	39.3	FfE SigLinDe [82], synthetic load profiles [84] [1]
Private and Public Services	28.3	22.3	18.3	FfE SigLinDe [82], synthetic load profiles [84] [1]
Agriculture	3.2	3.2	3.2	FfE SigLinDe [82], synthetic load profiles [84] [1]
Industry	102.0	94.5	86.4	FfE SigLinDe [82], combined industrial load profile [83] [1]

[1] in some cases without seasonal component. [2] Outside temperature additionally taken into account for heating/cooling demand.

Table A11. Consumption of the energy supply system for the scenario *Sufficiency* final energy (based on [40]).

Type	Energy Consumption 2030 in TWh/a	Energy Consumption 2040 in TWh/a	Energy Consumption 2050 in TWh/a	Used Profile
Transformation Losses	17.1	18.5	21.5	According to consumption
Transport Losses	6.7	6.9	6.9	Assumed as proportional according to generation and consumption
Consumption of Sector Energy	17.2	16.1	13.3	Assumed as constant
Non Energy Use	21.5	20.0	18.6	Combined industrial load profile [83] [1]

[1] Without seasonal component.

Table A12. Parameter of the used storages in the scenario *Sufficiency*.

Type	Capacity in GWh_{el}	Max. Charging Power in GW_{el}	Max. Discharging Power in GW_{el}	Cycle Efficiency	Losses over Time
Battery Storage	2.1–11.8 [1,2]	1.1–5.9 [2,3]	1.1–5.9 [2,3]	0.9	0 [4]
Pumped Storage	160 [37]	1.2–3.6 [2,5]	1.4–4.3 [2,5]	0.8	0 [4]

[1] Capacity calculated based on [87] corresponding to the photovoltaic rooftop expansion. Photovoltaic rooftop is about 40% of total photovoltaic potential (Table 1) [25]. [2] Range covers the difference considering the years between 2030 (min value) and 2050 (max value). [3] Typical ratio between capacity and power for commercial and industrial photovoltaic storages is chosen [88]. [4] Due to the short storage period, the losses over time are neglected. [5] Power is increased over time until maximum expansion ([37]) is reached.

Table A13. Conversion efficiencies of the scenario *Sufficiency*.

Conversion Unit.	Energy Efficiency
Fuels from hydrogen	η = 0.77 [89–92]
Gas fired power plant	η = 0.60 [93,94]
Biomass fired CHP	η_{el} = 0.28, η_{th} = 0.57 [37]
Electrolysis	η = 0.65–0.70 [1] [85]

[1] Range covers the difference considering the years between 2030 (min value) and 2050 (max value).

Table A14. Energy consumption of cars and trucks in the scenario *Sufficiency* (calculated values based on [25,47]).

Type	Internal Combustion Engine Drive in kWh/100 km	Battery Electric Drive in kWh/100 km	Fuel Cell Drive in kWh/100 km
Cars	68.8	21.7	36.5
Light-Duty Trucks	85.5	24.1	40.6
Medium-Duty Trucks	192.5	85.3	125.3
Heavy-Duty Trucks	337.9	169.4	248.9

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APPENDIX B: FURTHER SCIENTIFIC PUBLICATIONS

Spatially resolved renewable potential and demand

Moser, Simon; Goers, Sebastian; de Bruyn, Kathrin; Steinmüller, Horst; Hofmann, Rene; Panuschka, Sophie; Kienberger, Thomas; Sejkora, Christoph; Haider, Markus; Werner, Andres; Brunner, Christoph; Fluch, Jürgen; Grubbauer, Anna (2018): Renewables4Industry. Abstimmung des Energiebedarfs von industriellen Anlagen und der Energieversorgung aus fluktuierenden Erneuerbaren. Diskussionspapier (Endberichtsteil 2 von 3).

Sejkora, Christoph; Kienberger, Thomas (2018): Dekarbonisierung der Industrie mithilfe elektrischer Energie? In: Technische Universität Graz (Hg.): 15. Symposium Energieinnovation.

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Potential and demand of renewable gases

Sejkora, Christoph; Rahnama Mobarakeh, Maedeh; Hafner, Sarah; Kienberger, Thomas (2018): Technisches Potential an synthetischem Methan aus biogenen Ressourcen. Lehrstuhl für Energieverbundtechnik. Leoben.

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Multi Energy Systems and Energy Grids

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Discrete Fourier transform

Sejkora, Christoph; Pfeifer, Andreas; Kriechbaum, Lukas; Kienberger, Thomas (2019): Optimal linking of heat flows based on the discrete Fourier transform. Montanuniversitaet Leoben (11. Internationale Energiewirtschaftstagung an der TU Wien).

Electromobility

Vopava, Julia; Sejkora, Christoph; Thormann, Bernd; Kienberger, Thomas (2018): Nachhaltige Versorgung regionaler Elektromobilität aus regionalen erneuerbaren Ressourcen. In: WING-Business (1/2018), S. 20-24.

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Digitalization in Industry

Hofmann, René; Halmschlager, Verena; Knöttner, Sophie; Leitner, Benedikt; Pernsteiner, Dominik; Prendl, Leopold; Sejkora, Christoph; Steindl, Gernot; Traupmann, Anna (2020): Digitalization in Industry - an Austrian Perspective. Whitepaper. Hg. v. Climate and Energy Fund. TU Wien, Faculty of Mechanical and Industrial Engineering; TU Wien, Faculty of Informatics; TU Wien, Faculty of Electrical Engineering and Information Technology; AIT Austrian Institute of Technology, Center for Energy; Montanuniversitaet Leoben, Department of Environmental and Energy Process Engineering. Vienna, Austria.