



Review

Are we ready to plan for synergies? System Integration Impact Assessment in the Austrian energy system modelling community

Fabian Schipfer^{a,b,*}, Michael Harasek^a, Shubham Tiwari^b, Florian Kraxner^b, Johannes Schmidt^c, Sebastian Wehrle^c, Neda Asasian Kolor^a, Daniela Thrän^d, Danial Esmaeili Aliabadi^d, Hanna Breunig^e

^a Institute of Chemical, Environmental and Bioscience Engineering, Thermal Process Engineering - Computational Fluid Dynamics, Technische Universität Wien, Getreidemarkt 9/166, A-1060, Vienna, Vienna, Austria

^b International Institute for Applied Systems Analysis (IIASA), Agriculture, Forestry, and Ecosystems Services Group, Laxenburg, Austria

^c BOKU University of Natural Resources and Life Sciences (Boku), Institute of Sustainable Economic Development, Vienna, Austria

^d Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany

^e Lawrence Berkeley National Laboratory (LBNL), Berkeley, United States



ARTICLE INFO

Keywords:

System integration
Sector coupling
Nexus thinking
Network integration
Industrial symbiosis
Flexibility
Climate risk
Emergence

ABSTRACT

Integrated solutions across processes, sectors, and systems can deliver value that exceeds the sum of their parts. Sector coupling, for example, is increasingly recognized as a key enabler for balancing intermittent renewable electricity, while creating new interdependencies and systemic risks. Yet, the capacity of energy system models to anticipate such synergies and trade-offs remains uneven. This article presents a structured review of Austria's energy system modelling landscape, mapping over 800 publications from 54 research groups. We classify modelling capacities across technical, temporal, and spatial integration dimensions and identify significant gaps in areas such as bioenergy, circularity, and extreme event modelling, alongside promising advances in heating networks, electricity sector coupling, and energy communities. The growing attention to operational flexibility in long-term models offers a window of opportunity to better anticipate shocks, structural breaks, and resilience considerations. The openly shared integration fitness tables derived from this review aim to foster collaboration and capacity-building across modelling silos. We argue that advancing System Integration Impact Assessment requires uncertainty-aware modelling frameworks capable of capturing synergies, trade-offs, and systemic risks. Embracing uncertainty rather than reducing it can help design transformation pathways that are not only sustainable but also robust and flexible. Ultimately, this shift could bring together environmental and economic efficiency, safety, and security into a shared paradigm, elevating sustainable development toward reliable development.

1. Introduction

1.1. Background

Since the 1970s, modelling capacities for the Earth system have evolved around representing atmospheric circulations, while modelling

of the human system has focused on fossil fuel deployment [1,2]. During the first oil crisis, Energy System Models (ESMs) emerged to test least-cost energy security policies. Over time, their focus shifted toward anticipating carbon dioxide (CO₂) emissions from energy use and exploring pathways to achieve an economy-wide, carbon-neutral energy supply [3]. In the following decades, computer-aided quantitative

Abbreviations: 3D, Three dimensions; ABM, Agent-Based Modelling; CGE, Computational General Equilibrium; CO₂, Carbon Dioxide; DHC, District Heating and Cooling; IEA TCP, International Energy Agency Technology Collaboration Programme; IO, Input-Output Modelling; LCA, Life Cycle Assessment; LCC, Life Cycle Costing; NECP, National Energy and Climate Plans; NREL, National Renewable Energy Laboratory; ÖNIP, Austrian Integrated Infrastructure Plan; PV, Photovoltaic; SDGs, Sustainable Development Goals; SSPs, Shared Socioeconomic Pathways.

* Corresponding author at: Institute of Chemical, Environmental and Bioscience Engineering, Thermal Process Engineering - Computational Fluid Dynamics, Technische Universität Wien, Getreidemarkt 9/166, A-1060, Vienna, Vienna, Austria.

E-mail address: shipfer@iiasa.ac.at (F. Schipfer).

URL: <https://www.schipfer.eu> (F. Schipfer).

<https://doi.org/10.1016/j.erss.2025.104505>

Received 11 February 2025; Received in revised form 23 November 2025; Accepted 6 December 2025

Available online 24 December 2025

2214-6296/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

scenario modelling became increasingly central to policymaking worldwide. This is evidenced by its institutionalization through the founding of international organizations such as the International Energy Agency¹ (IEA) in 1974 and the Intergovernmental Panel on Climate Change² (IPCC) in 1988, both of which place long-term energy and climate assessment at their core.

As a result of this historical trajectory, the policy modelling landscape has become largely focused on potential changes in the energy system, particularly emphasizing cost efficiency and greenhouse gas (GHG) reductions. This focus has made it difficult for other critical topics to achieve comparable institutional and methodological maturity or recognition in policymaking. Recent high-level reviews and reports highlight, for example, the limited integration of bioenergy [4], the broader bioeconomy including food and biobased material provision [5] and hydrogen [6] into established modelling infrastructure. In a recent paper, several potential low-hanging fruits are identified, such as CO₂ networks, heat grids, material trade networks, and various forms of storage and flexibilization beyond electricity, that could be integrated into existing energy system modelling frameworks at low cost to significantly expand their scope [7].

More complex than simply adding missing energy system functions may be the challenge of “coupling circularity performance and climate action,” as advocated by Nikas et al. [8], who propose a novel transdisciplinary modelling paradigm to support multisector integration. Taking an even broader view, the Alliance of Sustainable Universities in Austria emphasizes an interdisciplinary agenda that considers interactions among all 17 Sustainable Development Goals (SDGs), rather than focusing solely on ‘climate action’ and ‘clean energy for all’ [9].

In 2016 and 2017, a high-level report by the U.S. National Renewable Energy Laboratory (NREL) [10], along with a journal paper collection and guest editorial [11], described how a wide range of energy system planning aspects can be jointly addressed under the concept of ‘system integration’. These publications recognized the ‘value proposition’ of integrated systems in ‘unlocking flexibility.’ Interconnecting various energy domains, jointly considering operation and planning, and addressing different geographical scales enable the coordinated, reliable, cost-effective, and environmentally sound balancing of energy resources [11].

However, based on discussions and publications from the International Energy Agency Bioenergy Technology Collaboration Programme (IEA TCP)—which dedicates a Task³ to ‘flexibilization and system integration’—we must acknowledge that some aspects of system integration are more readily implemented in existing models than others. In particular, the flexibility arising from the versatility of bioenergy practices remains a challenging candidate [12]. To the best of our knowledge, a comprehensive review assessing the readiness of modelling practices for taking into account system integration impacts is still lacking. An initial global search in Scopus for publications with ‘energy system integration’ in the title, abstract, or keywords yielded 348 research papers and 33 reviews covering a wide range of topics.⁴ Frequently cited international publications focus on areas such as energy communities [13], smart cities [14], distributed multi-energy systems [15], the energy-water nexus [16], energy storages [17], and the potential of energy system flexibilization through power sector coupling [15].

1.2. Outline and contributions of this review

Our unique contribution lies in the structured review of the *Modelling Readiness Level* [18] for various aspects of system integration. We

therefore pose the question: how well are existing models equipped to anticipate the synergies and trade-offs of integrated versus isolated processes, systems, networks, economic sectors, and societal goals? With this, we aim to advance a novel field of *System Integration Impact Assessment* by raising awareness of the value propositions associated with system integration. We derive valuable insights into the historical context, current focus areas, and the opportunities and barriers to unlocking flexibility for the coordinated, reliable, cost-effective, and environmentally sustainable balancing of energy and other resources.

The methodology section begins by defining system integration and distilling its core value propositions. We then describe the review methodology, which we apply to our case study region—Austria. While this study is geographically limited, the methodology is designed to be applicable to other and larger regions in future research. We deliberately chose Austria for this initial case study to enable a quasi-comprehensive mapping of research groups actively engaged in a wide range of energy modelling topics. Austria is a member of the IEA and the IPCC and plays a leading role in international collaborations such as the European Climate and Energy Modelling Forum (ECEMF) and the Integrated Assessment Modelling Consortium (IAMC). Its relatively small size—representing only 2 % of the European Union's population [19]—makes it feasible to assess the national energy system modelling landscape comprehensively and to position Austria's modelling ecosystem as a suitable first case study. Furthermore, recent national policy discussions in Austria have emphasized the need for greater system integration, raising the question of whether the existing modelling ecosystem is adequately equipped to support integration planning.

In the results and discussion section, we first present a structured overview of the identified system integration aspects, and the modelling capacities observed in the case study. While the review is centered on economy-wide energy system scenario modelling, it also highlights opportunities for interdisciplinary learning and cross-fertilization from other fields that are relevant to modelling system integration impacts. We then place the case study findings in an international context to assess their generalizability. Finally, we summarize the *Modelling Readiness Level for System Integration Impact Assessment* based on the Austrian case study, identifying key development opportunities and barriers. Additionally, we provide the results of our mapping exercise to the research community in the form of downloadable spreadsheets, enabling quick identification of complementary skills.

2. Methodology

2.1. Understanding ‘system integration’ (Stage 0)

We build on the definition of *Energy System Integration (ESI)* by O'Malley and Kroposki [11]:

“ESI is the process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment.” [11]

By unpacking this definition, we aim to make it more actionable. It highlights three key dimensions of coordination: a **technological** dimension through “multiple pathways,” a **temporal** dimension through “operation and planning,” and a **spatial** dimension through “multiple geographical scales.” Additionally, the definition outlines objectives that go beyond economic and environmental efficiency to include resilience and reliability. Each of these three dimensions encompasses a wide range of topics, which we explore in our review:

- **Technical or sectoral integration impacts** arise when different physical resources, processes, systems, and networks are coupled. Cross-connectors, such as conversion technologies, heat exchangers, and infrastructure links, enable this integration. Examples include supporting intermittent renewable electricity generation with gas-

¹ <https://www.iea.org/about/history> accessed 10.02.2025.

² <https://www.ipcc.ch/about/history/> accessed 10.02.2025.

³ <https://task44.ieabioenergy.com/> accessed 10.02.2025.

⁴ <https://www.scopus.com/> search on 08.12.2024.

fired power plants and power-to-gas technologies, which connect gas and electricity grids [20]; electrification strategies in the transportation and heating sectors [21,22]; and the efficient implementation of combined heat and power plants [23]. Additional cross-connectors include high-temperature heat pumps for industrial electrification [24], as well as bioenergy, hydrogen, and CO₂ management strategies in industrial networks [25]. Broader still, the *water-energy nexus* addresses the impact of cooling systems in nuclear and thermal power plants, reservoir-based hydropower, bioenergy supply, and hydrogen synthesis on water systems [26].

- **Temporal integration impacts** occur when strategic, long-term developments are considered alongside short-term and operational aspects, while also accounting for shocks, events, and recovery processes. Temporal cross-connectors include all forms of storage, savings, redundancies, and backups. Examples include various energy storage technologies, such as pumped hydro, compressed air, hydrogen, batteries, flywheels, and supercapacitors, designed to shift energy surpluses to cover shortages over minutes, hours, days, or even seasons [27]. Biomass and bioenergy carriers (e.g., straw bales, wood pellets, pyrolysis oil, ethanol, biogas, biomethane) are often stored in low-cost, low-tech ways that contribute to seasonal energy security, and are increasingly considered for short-term balancing as well [12]. Thermal energy storage, whether sensible, latent, or thermochemical, is discussed in the context of concentrating solar power [28] and residential heating, including the thermal storage potential of buildings [29].
- **Spatial integration impacts** emerge when physical resources, processes, systems, and networks are coupled across different locations. Again, cross-connectors such as conversion technologies and infrastructure links play a key role. Energy system models vary in spatial scope, from regional to global, and in their resolution of “nodes,” which may represent municipalities, countries, or world regions [30]. Spatially resolved studies often inform the potential for biomass, photovoltaic, and wind energy production, as reviewed by Martínez-Gordón et al. [31]. However, detailed representations of nodes and edges are more commonly found in network expansion studies [32] and bioenergy supply chain research [33]. Multi-level governance involves integration across different tiers of government, from municipal to provincial and national levels [34]. Energy communities can provide autonomy to stakeholder groups embedded within national markets [13]. Social aspects at the individual level, such as behavior, lifestyle, actor heterogeneity, public acceptance, participation, and ownership, are typically addressed using Agent-Based Models (ABMs) [35].

2.2. Building a bibliometric dataset of relevant publications (Stage 1)

The objective of Stage 1 was to identify publications by researchers who are currently or were recently affiliated with Austrian institutions and are actively publishing on topics relevant to integrated energy system modelling. For this purpose, we used the relatively new *Author Discovery* functionality provided by the Scopus database.⁵ We restricted the searchable corpus to publications with an Austrian affiliation from 2020 onward. To broaden the scope beyond the limitations of a narrow keyword search, we reviewed the complete publication lists of each identified author using both Scopus and OpenAlex. This approach significantly reduced the bias introduced by a limited set of search terms or database.

From an initial pool of approximately 4000 titles, we identified 863 unique publications. Their bibliometric data were downloaded in BibTeX format and imported into the reference management tool *EndNote* 21™.

A large portion of the dataset (465 unique publications) was

identified using the term *energy system*. These publications cover a wide range of topics, including electricity and gas grids, fossil fuels, hydropower, photovoltaics, and other renewable energy sources. However, this search alone missed authors working on related topics such as *bio-energy*, *biomass*, and *waste*, which contributed an additional 133 publications to the final dataset.

In previous work [7,12], we emphasized *resilience* and *reliability* as key aspects of system integration. To capture related research, we also used the keywords *risk* and *uncertainty*. However, these terms primarily returned publications from the medical and biotechnological fields. In contrast, the term *disaster* was more commonly associated with research on natural hazards. We identified 161 publications using this term, which we included for further analysis regarding their relevance to integrated energy infrastructure planning. The term *risk management* yielded another 51 unique publications, mostly focused on safety and security in technical systems—topics that are also potentially relevant for energy systems. Finally, 17 additional publications were identified using the term *tipping point*.

The full list of publications is provided in the Supplementary materials. The review methodology and how Stage 1 links to the next Stage 2 and Stage 3 is illustrated in Fig. 1.

2.3. Quasi-comprehensive mapping of Austrian research groups (Stage 2)

The objective of Stage 2 is to map Austrian research groups and affiliations that are, or could be, relevant to integrated energy system modelling—focusing on their modelling expertise and national and international co-authorship networks.

To achieve this, we extended the BibTeX file with additional metadata, including abbreviations for each research institute and the specific group within the institute associated with the most prominent Austrian-affiliated author of each publication. We used the R *Bibliometrix* package⁶ to cluster Austrian-affiliated authors and, in a later step, to analyze collaboration networks between research groups.

We further enriched the BibTeX file by adding columns that describe the thematic focus of each publication using a standardized set of keywords. For this, we used the *EndNote* 21™ software⁷ to create and apply tags to each abstract. Each abstract was tagged with one or more keywords. While individual abstracts may not always provide sufficient detail for precise categorization, tagging over 800 publications with 21 distinct keywords yields representative distributions that offer valuable insights when analyzed bibliometrically.

We grouped the 21 keywords into thematic clusters relevant to system integration dimensions:

- **Technical dimension:**
Resources group (14 keywords): e.g., electricity, bioenergy, heat
Sectors group (7 keywords): e.g., industry, mobility, housing
- **Spatial dimension:**
Spatial group (6 keywords): e.g., *national*, *region*, *supply chains*
- **Temporal dimension:**
Temporal group (5 keywords): e.g., *strategic*, *operation*, *event*

Additionally, we reserved a separate column for six *focus keywords* to flag whether a publication explicitly addresses topics such as *integration*, *flexibility*, or *uncertainty*.

The intermediate output of Stage 2 is a spreadsheet that enables filtering and ranking of researchers or research groups based on the number of tagged publications in the bibliometric dataset (see Supplementary materials). This spreadsheet provides a statistical overview of the most active authors and groups, along with their thematic focus areas. It also allows for visual identification of integration gaps and

⁵ <https://scopus.com/> accessed 17.10.2024.

⁶ <https://www.bibliometrix.org/home/> accessed 17.10.2024.

⁷ <https://endnote.com/de/product-details/> accessed 17.10.2024.

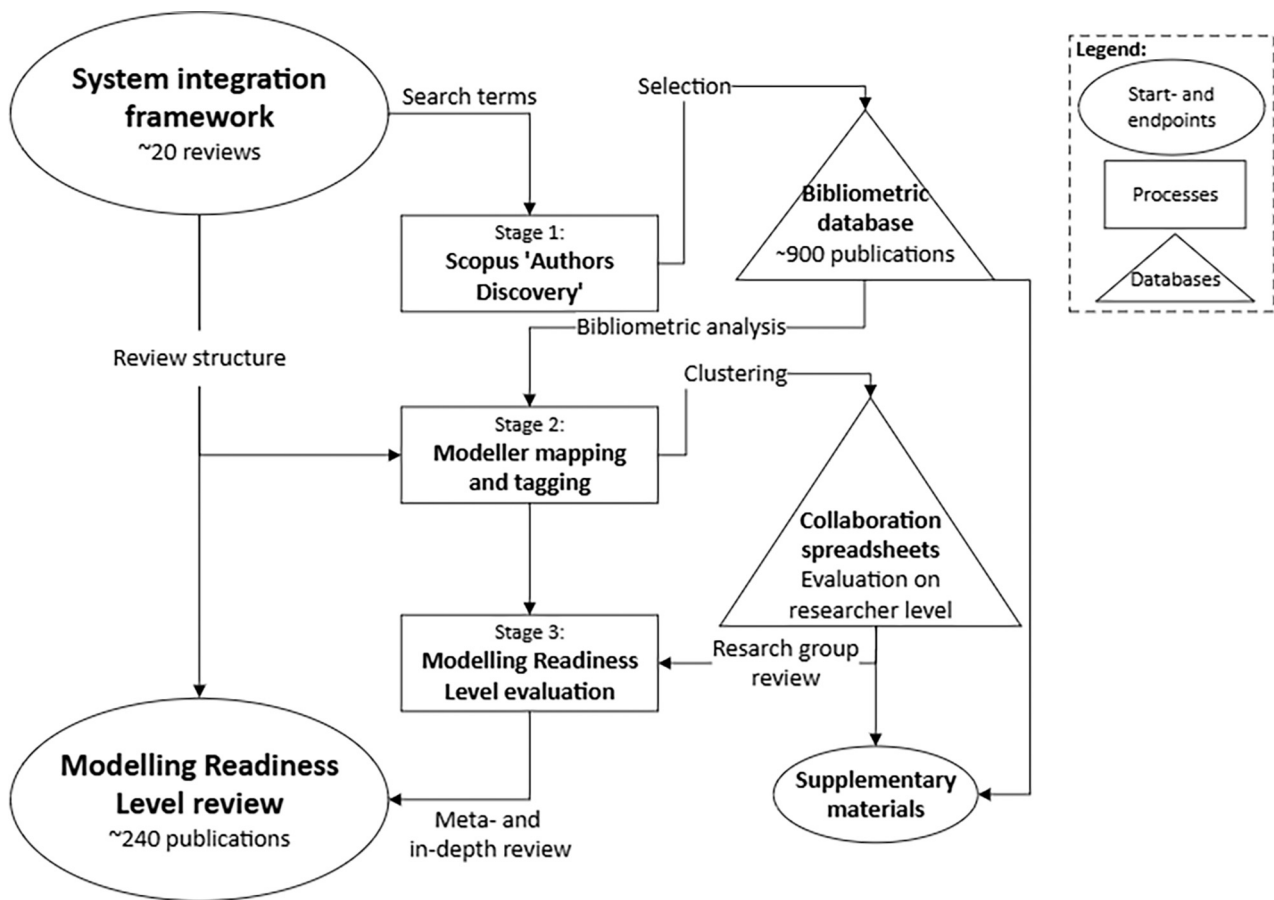


Fig. 1. Presents a flow diagram illustrating the methodology of multi-stage meta-analysis and in-depth review. Source: own illustration.

collaboration opportunities across the Austrian modelling landscape. The large number of analyzed abstracts help mitigate minor inconsistencies in the tagging process.

2.4. Modelling Readiness Level (MRL) evaluation of system integration aspects (Stage 3)

In Stage 3, we build upon the structured framework and comprehensive overview table developed in Stage 2 to guide the aggregation, representation, and evaluation of the bibliometric dataset. To qualitatively assess current modelling capabilities for addressing various aspects of system integration, we adapt the *Modelling Readiness Level (MRL)* framework proposed by Hammerschmid et al. [18]. Originally developed for process models, the MRL framework consists of nine levels—modelled after the Technology Readiness Levels (TRLs)—culminating in “digital predictive twins” that are fully implemented and actively support the operation of commercial plants.

In contrast, energy system models primarily serve to inform the strategic development of economy-wide infrastructure, including generation fleets, reserves, and cross-border trade. Unlike process-level systems, the complexity, scale, and socio-technical nature of entire economies make the concept of a fully operational digital twin currently infeasible. Accordingly, we reinterpret the MRL framework as a qualitative and relative metric that offers a structured, yet inherently subjective, evaluation of a modelling approach's preparedness for practical deployment and decision-making.

Our adapted MRL assessment is based on the following five criteria:

- **Adoption by the research community:** The degree of establishment and standardization of modelling practices, including documentation and acceptance.
- **Data availability:** The accessibility, quality, comprehensiveness, and spatial/temporal resolution of relevant data.
- **Calibration potential:** The extent to which models can be calibrated using historical or empirical data.
- **Transferability to practice:** The ability of the model to generate actionable insights and inform operational strategies.
- **Commercialization and application status:** The extent to which models and algorithms are integrated into commercial tools, products, or real-world applications.

Finally, we contextualize the case study results within the broader international landscape to assess their generalizability. This comparative perspective allows us to identify common patterns and divergences across different modelling environments. We then synthesize the *Modelling Readiness Level for System Integration Impact Assessment* as demonstrated in the Austrian case study, highlighting key development opportunities and barriers to broader implementation.

3. Results and discussion

3.1. Energy system modelling in Austria – a weakly linked community of experts

Our curated dataset includes publications from 54 research groups across 25 institutes and universities. A full list of these groups, their affiliations, and abbreviations is provided in Table 2 in the Annex. Fig. 2 illustrates the clustered co-authorship network among these research

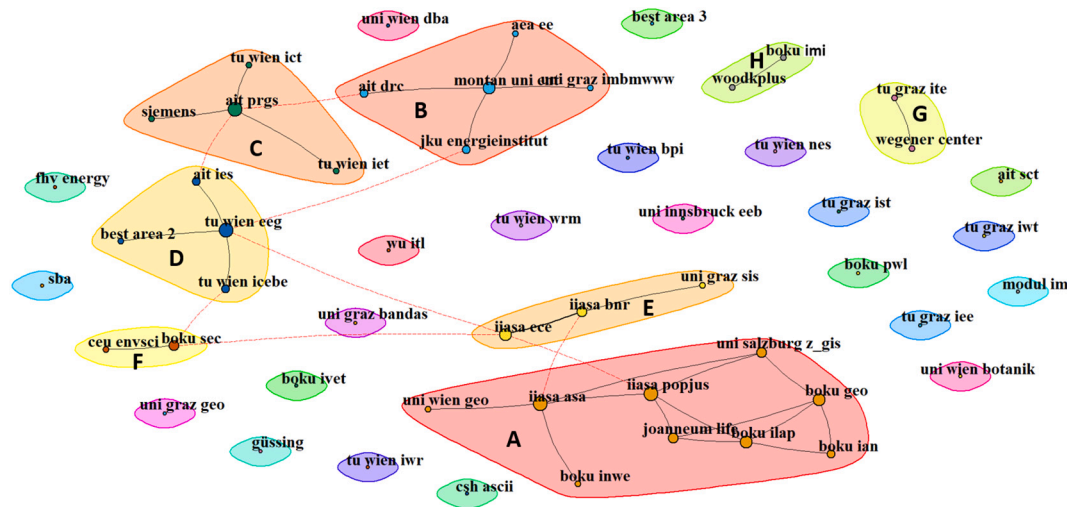


Fig. 2. Co-authorship network of Austrian research groups relevant to integrated energy system modelling. Source: own illustration using the R Bibliometrix package.

groups. The bibliometric analysis reveals weak co-authorship links between many groups, indicated by single joint publications (dotted red lines), and stronger links where multiple joint publications exist (black lines, clustered within colored circles).

The largest collaboration cluster—**Cluster A**—shows ongoing cooperation among nine research groups, primarily from the University of Natural Resources and Life Sciences (BOKU) and the International Institute for Applied Systems Analysis (IIASA). However, these groups currently focus more on climate risk and disaster risk management than on energy systems. We discuss the relevance of their modelling approaches for energy system applications in [Section 3.3](#).

Cluster B highlights collaboration between Montan Universität Leoben (Montan Uni), Johannes Kepler Universität Linz (JKU), and the Austrian Institute of Technology (AIT), with a focus on long-term energy strategies for Austrian industries (see [Section 3.2.6](#)). AIT also appears in **Clusters C and D**: Cluster C is more process-modelling-oriented (AIT, TU Wien, Siemens GmbH; see [Section 3.2.1](#)), while Cluster D is more system-modelling-focused (AIT, TU Wien, and Bioenergy and Sustainable Technologies GmbH (BEST); see [Section 3.2.8](#)). TU Wien also connects to **Clusters E and F**, which focus on integrated assessment modelling ([Section 3.2.9](#)), with one cluster centered around IIASA and the other around BOKU.

Overall, [Fig. 2](#) reveals a large but weakly interconnected community of energy system modelling groups in Austria. Fewer than half of the identified groups appear to collaborate with one another. Even within large universities, collaboration between individual research groups is limited. Only a few groups—particularly at IIASA, TU Wien, BOKU, and Montan Uni—show co-authorship links with more than four other Austrian-based groups.

The bibliometric analysis summarized in [Table 1](#) provides an overview of publication activity since 2020, categorized by integration dimensions and sectoral focus (housing, industry, mobility, and multi-sector).

The data presented in [Table 1](#) highlight several key characteristics of the Austrian energy system modelling landscape. Most notably, there is a pronounced concentration of research activity in the housing sector, particularly in the context of regional modelling of strategic heating transitions. These models frequently incorporate multiple energy vectors, such as heat, electricity, natural gas, and bioenergy, and span a range of spatial scales, from regional to national and international levels. This suggests a well-established modelling capacity for assessing residential heating strategies within integrated energy systems.

A second area of strength lies in multi-sector modelling at national and international scales, with a strong emphasis on the electricity sector

Table 1

Occurrence of publications for selected topic combinations in our literature dataset. Source: own evaluation based on the BibTeX file in the Supplementary materials.

	Multi-sector	Housing	Industry	Mobility
Technological dimension				
Multi-resource	7	26	6	2
Electricity	23	40	18	20
Heat	6	63	15	1
Bioenergy	8	9	9	5
Other	11	11	10	8
Temporal dimension				
Multi-temporal	4	5	1	3
Strategic	57	50	13	16
Operational	12	25	23	13
Events	7	3	5	6
Spatial dimension				
Multi-spatial	7	15	4	4
International, national	43	47	22	17
Supply chains, networks	11	20	12	21
Regional, local	36	63	19	16

and its role in the electrification of heating, mobility, and industrial processes. However, the data also reveals a relatively low ratio of operational to strategic modelling within this category, in contrast to the housing sector, where operational aspects are more frequently addressed. Notably, a significant subset of multi-sector publications adopts a regional or local perspective, indicating growing interest in decentralized energy planning. These findings underscore the increasing importance of flexibility measures to address the variability of renewable electricity generation and highlight the methodological challenges of integrating operational dynamics into strategic models. While the concept of energy communities is beginning to gain traction among Austrian research groups, their integration into national, economy-wide energy system models remains limited.

In contrast, the modelling of energy systems for the industrial and mobility sectors is comparatively underdeveloped. In the case of industry, we include process engineering models that focus on plant-level operations, which offer valuable insights for two purposes: (1) informing strategic, economy-wide industry modelling, and (2) adapting process integration methods for broader system integration. The mobility sector is even less represented, with relevant publications primarily addressing supply chains, road networks, charging infrastructure, and the role of electric vehicle fleets as distributed storage assets.

Finally, temporal integration remains the least developed dimension

across the dataset. This is particularly noteworthy given that temporal integration is essential for evaluating whether technical and spatial integration efforts achieve their intended benefits in terms of system reliability. The limited attention to temporal dynamics is surprising and suggests a critical gap in current modelling practices. In Section 3.4, we further explore this issue by outlining a potential trajectory for the evolution of international energy system modelling—from a historical focus on long-term uncertainties, toward the integration of short-term operational variability, and ultimately, the incorporation of disruptive and extreme events.

3.2. Energy system modelling integration opportunities and challenges

Table 2 introduces a range of system integration aspects and presents their corresponding *Modelling Readiness Levels (MRLs)*, as assessed for the Austrian energy system modelling community. These MRLs reflect the current state of modelling capabilities to capture integration impacts across technical, temporal, and spatial dimensions. The evaluation is based on representative modelling groups and collaborations identified in our case study, along with relevant references.

The following subsections (Sections 3.2.1 to 3.2.9) provide a detailed discussion of each integration aspect, including the rationale behind the assigned MRL, illustrative modelling examples, and key opportunities and challenges for advancing integration readiness.

3.2.1. Process heat integration

Process intensification and heat integration represent some of the earliest engineering domains to quantitatively model the impacts of energy flow integration. The industrialization of many world regions during the fossil fuel era was driven by efforts to reduce heat losses, supported by advances in the numerical and graphical representation of heat flows—most notably through Sankey diagrams [227]. While our focus lies on economy-wide energy systems rather than individual industrial processes, this well-established domain offers valuable methodological insights for broader system integration.

In the Austrian context, two research groups are selected to represent

Table 2
Modelling Readiness Levels (MRLs) of different system integration aspects based on the case study of the Austrian energy system modelling community. Source: own evaluation.

MRL	System integration aspects	Modelling groups and collaborations	References
High	Process heat integration	TU Wien IET TU Wien ICEBE	[36–51] [52–55]
Medium	Heating network modelling	TU Wien EEG Uni Innsbruck	[56–67] [68–74]
High - Medium	Electricity sector coupling	TU Graz IIE TU Wien EEG Boku INWE TU Wien BPI	[75–82] [64,83–94] [95–97] [98–102]
Medium	Electricity and gas grid optimization	TU Graz IIE	[76–78,103,104]
Low but growing fast	Energy community integration	TU Wien EEG, AIT IES, BEST TU Wien ICT TU Wien NES AIT DRC	[86,92,105–121] [122–127] [128–134] [135,136]
Low	Multisector coupling - industry	AIT IES, Montan Uni, JKU Wegener Center	[137–149] [150–153]
Low	Multisector coupling - circularity	BOKU SEC TU Wien IWR Uni Graz ITE WU Wien	[154–164] [165–177] [178–186] [187–189]
Low	Hybrid energy systems - bioenergy	IIASA BNR BEST, TU Graz IRT	[190–207] [208–215]
Low	Energy-food-water nexus	IIASA ECE, IIASA BNR	[216–226]

the field of process integration: TU Wien IET [36–51], which focuses on integrating different heat levels in sectors such as iron and steel production, and TU Wien ICEBE [52–55], which specializes in thermochemical process integration, for example in gasification systems for biofuel production. A particularly promising concept for transfer from process to system engineering is *Heat Exchanger Network Synthesis (HENS)*. HENS optimizes variable stream temperatures and flow capacities to enhance heat integration in industrial plants [42]. It has been applied to identify synergies in hydrogen, synthetic natural gas, and ammonia production in steel mills [51], to plan heat exchange network refurbishment [41], and to retrofit multi-period heat exchanger networks in the process industry [48].

HENS is a mature methodology, particularly in the temporal integration of intermittent process heat levels at the plant scale. Its capacity to estimate the impact of integrating multiple energy vectors makes it highly relevant for broader energy system modelling. Knöttner and Hofmann [228] highlight the intersection between electricity sector flexibility and the planning of integrated, flexible industrial energy systems. They provide an overview of industrial energy flexibility, associated incentives, and its integration into the decision variables, constraints, and objectives of mathematical optimization models.

Flexibility in process engineering is typically addressed through operational optimization and energy storage, including the conversion between multiple energy carriers. This is achieved by combining four functional units: conversion, storage (thermal and mass), input, and output [38], as well as through integrated energy and production scheduling [39]. These approaches offer conceptual bridges to modelling intermittent renewable electricity at the sectoral level.

Practical relevance is further demonstrated by Austrian contributions to the International Energy Agency (IEA) Industrial Energy-Related Technologies and Systems (IETS) Technology Collaboration Programme (TCP), particularly in the identification, quantification, and operational recovery of excess heat in industry [229]. Through system synthesis, design, and operation, industrial energy supply systems are increasingly optimized with consideration for district heating integration [44].

We assess the MRL for process integration in Austria as high, particularly with respect to the temporal integration of intermittent process heat. HENS and its derivative tools offer significant potential for informing system-level modelling of integration and flexibility. Their application at the industrial site level benefits from excellent data availability and strong industry engagement, providing empirical validation of how integrated energy flows can enhance system efficiency and reliability.

3.2.2. Heating network modelling

District heating (DH) networks offer a means of connecting industrial waste heat to surrounding residential areas. Unlike process integration at a specific industrial site, DH modelling presents distinct challenges related to data availability, spatial resolution, and implementation, particularly due to the involvement of numerous heterogeneous decision-makers, such as households. Consequently, the primary focus of DH modelling lies in spatial integration.

Representative Austrian research groups in this domain include TU Wien EEG [56–67] and the University of Innsbruck [68–74]. Expansion modelling for district heating and cooling networks (DHCNs) in Austria [58] and at the European level [56] is typically based on spatially explicit mapping exercises. Recent work has also addressed the integration of process cooling into district cooling networks [59–61], contributing to scenario development for cooling energy demand in Austria through 2050 under varying climate conditions, and analyzing the aggregated impact of cooling options on the electricity grid [62,63].

Spatial matching techniques combine diverse datasets to identify industrial excess heat potentials for district heating [57] and explore the use of industrial excess cooling for residential applications [59]. Bespoke models have been developed for investment portfolio optimization in Austrian DH utilities, including the integration of heat pumps

[64], and for evaluating business models for biomass-based DH systems under flexible heat demand conditions [65]. Internationally, DH network expansion modelling has been implemented in the *EMPIRE* model for Norway [66], while spreadsheet-based tools have been used to assess heating and cooling storage needs under renewable electricity scenarios for selected countries [67].

We estimate the MRL for district heating network modelling in Austria to be medium. Current modelling efforts are well-established in the spatial integration of heat flows for residential heating—and increasingly, residential cooling. The spatial matching of industrial waste heat sources with residential demand, along with spatially explicit network expansion planning, provides a methodological foundation that could be extended to other infrastructure networks, such as hydrogen, bioenergy supply, and CO₂ transport.

While industrial waste heat remains the traditional primary energy source for DH, recent publications indicate a shift toward sector coupling with the electricity system. The integration of heat pumps, flexible heating strategies based on intermittent renewable electricity, and associated storage requirements introduces new opportunities for combined spatial, temporal, and sectoral integration. DH modelling thus emerges as a promising platform for advancing system-wide integration strategies. Despite promising methodological advances, current heating network models lack validated demand data and robust spatial network representations, limiting their transferability to practice.

3.2.3. Electricity sector coupling

We define electricity sector coupling as the electrification of sectors that have traditionally relied on primary energy carriers other than electricity, most notably residential heating (with or without district heating networks) and mobility for personal and goods transport. Electrification options for these sectors are commercially available, and electricity system modellers are increasingly expanding their scopes to explore how sectoral integration can enhance the flexibility of electricity systems, particularly in accommodating intermittent renewable generation.

Representative Austrian research groups in this field include TU Graz IEE [75–82], TU Wien EEG [64,83–94], BOKU INWE [95–97], and TU Wien BPI [98–102]. A key development is the transfer of temporal integration methods from operational, process-focused electricity sector models to strategic, economy-wide system models. For example, the open-source *Low-carbon Expansion Generation Optimization (LEGO)* model combines short-term unit commitment with long-term generation and transmission expansion planning. *LEGO*'s development is informed by the techno-economic simulation model *ATLANTIS*, which integrates a physical model based on direct current load flow with an economic optimization framework [80]. *LEGO* is modular and temporally flexible, supporting thematic extensions such as battery storage, hydrogen integration, demand-side management in residential heating, and electric vehicle charging [79]. Future work on *LEGO* emphasizes time series aggregation to improve computational efficiency [81] and better incorporate network and ramping constraints [82].

From a more building operations perspective, the *CESAR-P* model—combined with *EnergyPlus*—has been applied to a Swiss building stock model to evaluate national-scale retrofit strategies [98]. This model is further integrated with the multi-objective optimization tool *Energy Hub* to test electrified flexibility solutions for grid services [99] and to derive uncertainty-aware flexibility envelopes [100]. Similar approaches using *TRNSYS* estimate synergies between battery storage, hydrogen storage, and residential heating [101]. Machine learning-based surrogate models have also been developed to enhance the computational performance of conventional retrofit models such as *Energy Hub* and the *Urban Building Energy Modelling (UBEM)* tool [102].

In contrast, sector coupling between the electricity and mobility sectors is less developed in Austria. Relevant studies address bidirectional charging infrastructure, electric car sharing, and on-site PV generation in residential buildings, often requiring Mixed-Integer Linear

Programming (MILP) frameworks [89]. The *EDisOn* model applies a four-step optimization approach to minimize dispatch costs while using electric vehicle fleets as flexible demand [90]. Fast-charging infrastructure along Austrian highways is planned using the *HighCharge* MILP model, which employs a node-based allocation approach based on traffic flows [91]. Hydrogen fuel production and storage are also optimized at microgrid laboratory facilities [92]. More detailed operational modelling, such as topography-based route planning for electric vehicles [93] and the aggregation of diverse driving profiles into electricity demand projections for the transport sector [94], is likely required to advance this area.

We estimate the MRL for sector coupling modelling in Austria to be relatively high for the electrification of residential heating, but lower for the mobility sector. Promising approaches are emerging from operational electricity system modelling and building energy simulation, both of which benefit from good data availability and calibration potential. However, integrating the mobility sector poses greater challenges due to the need for highly dynamic representations of heterogeneous decision-makers (i.e., drivers), combined with high temporal and spatial resolution across electricity networks, road infrastructure, charging stations, and households.

3.2.4. Integrating modelling of electricity and gas grids

The *Integrated Austrian Network Infrastructure Plan (ÖNIP)* simulates the operation of Austria's high-level electricity and gas networks under future conditions to assess integrated expansion requirements for both systems [230]. While this policy document plays a central role in infrastructure planning, it discloses remarkably little about its underlying data sources and modelling methodologies. Nevertheless, state-of-the-art approaches to integrated electricity and gas grid expansion modelling are reviewed by TU Graz IEE [76], and their insights have been applied to extend the *LEGO* model for flexible, integrated, sector-coupled energy system optimization. This includes a novel gas flow formulation to support the ramp-up of the hydrogen sector [78].

To our knowledge, TU Graz IEE is the only Austrian research group that credibly combines operational and strategic modelling expertise across both gas [76–78,103,104] and electricity networks (see previous section). For example, the multi-objective bi-level optimization model *GASMOPEC* has been applied to analyze investment options in natural gas pipelines and regasification terminals within the EU framework [103]. This model builds on operational and technical expertise in combined-cycle gas turbines and unit commitment modelling [104], and includes MILP-based modelling for optimal hydrogen feed-in through natural gas grid blending and transport [77].

We assess the MRL for integrated electricity and gas grid modelling in Austria as medium. While the modelling work of TU Graz IEE appears to inform national policy planning, only one research group is actively publishing in this area. Moreover, the ÖNIP itself appears to rely on a combination of isolated, stand-alone modelling approaches that do not fully capture integration impacts. Separate assessments are conducted for residential heating electrification, power-to-gas conversion, and various storage technologies. However, key integration mechanisms, such as demand-side management, curtailment, and the endogenous interaction between electricity and gas networks, are not comprehensively modelled.

Although the plan benefits from the operational expertise of the involved research group, it lacks a broader systems integration perspective and a structured evaluation of integration impacts. Advancing the MRL in this area will require more cohesive modelling frameworks that explicitly account for the synergies, tradeoffs, and threats of integrated electricity and gas infrastructures.

3.2.5. Energy community integration

Energy communities (ECs) offer a promising framework for integrating multiple levels of governance and decision-making. Introduced in 2019 through the EU's *Clean Energy for All Europeans Package*,

Renewable Energy Communities (RECs) enable energy sharing among households, municipalities, and small and medium-sized enterprises located in close proximity, as defined in Articles 2 and 22 of the second Renewable Energy Directive [231].

Despite their recent emergence, several Austrian research groups are already actively engaged in EC modelling. Notable contributors include AIT IES (often in collaboration with TU Wien EEG) [86,92,105–121], TU Wien ICT [122–127], TU Wien NES [128–134], and AIT DRC [135,136]. Early modelling efforts employ bespoke MILP-based models in MATLAB and Pyomo to develop business cases for energy supply contracting and energy sharing, accounting for electricity and heat loads in neighborhood-scale communities [111]. These models also explore the effects of CO₂ pricing on cost savings for ECs involving electric devices, vehicles, and heat pumps [112], and include peer-to-peer trading mechanisms with community battery storage [113].

Thermodynamic models combined with technology cost data are used to estimate the cost-saving potential of district heating temperature reductions [111,114], while inter-regional heating networks are explored for buffering energy price volatility and enhancing waste heat integration [115]. The *Resource Utilization in Sector Coupling* (RUTIS) framework supports the design of business models that extend beyond energy to include services such as waste disposal and water management [86,116].

Other bespoke models address the profitability of PV self-consumption [117], dynamic participation in peer-to-peer electricity trading [118], and the influence of foresight and forecasting on community member behavior and system performance [119,120]. Operational control strategies, such as *Model Predictive Control* (MPC), are applied to optimize the dispatch of flexible assets [121], and are also used in strategic expansion modelling, including for Austria's only microgrid laboratory facility [92].

Operational considerations are further extended to model flexibility offerings from prosumers and demand-side management [123] with corresponding signaling mechanisms [124,127]. MPC is also applied to mixed energy resources within individual ECs [122,126], and its impact is simulated on community-level energy balances [125]. A particularly promising approach that bridges operational and strategic modelling is the *LINK-based holistic architecture*, which minimizes data exchange requirements between ECs and electricity systems [131,133]. This architecture has also been applied to Positive Energy Districts [129] and to enhance power grid resilience through flexibility [128].

We assess the MRL for EC integration modelling in Austria as relatively low but rapidly advancing. A growing number of research groups are addressing diverse aspects of ECs. However, it remains to be seen how effectively these insights can support integrated planning across multiple governance levels—from individual households to communities, regions, and transnational energy systems. Moreover, recent project⁸ work has identified a notable blind spot in EC research: the limited attention to bioenergy, particularly biogas, which holds significant potential for community-building and local energy autonomy.

3.2.6. Multi-sector coupling – energy system and industry

While sector coupling, as discussed in Section 3.2.3, primarily addresses the electrification of the heating and transport sectors, many industrial processes remain classified as hard-to-abate. These processes often require high-temperature heat beyond the capabilities of current heat pump technologies, as well as carbon and other material inputs. As a result, industrial transformation is frequently treated as a distinct modelling challenge.

Representative Austrian research groups working on integrated energy system and industry modelling include a consortium of AIT IES,

Montan Universität Leoben, and JKU [137–149], as well as the TU Graz Wegener Center [150–153]. The Austrian energy model region *New Energy for Industry* (NEFI) envisions a climate-neutral industrial sector by 2040 [145,146]. Initial deep decarbonization scenarios for Austria's manufacturing industry have been developed, using sector-specific Sankey diagrams to identify opportunities for energy efficiency improvements, electrification, fuel switching, carbon capture and storage, and circular economy strategies [138,143,144].

Industry-specific studies include techno-economic assessments of CO₂ capture from cement and steel production, and its utilization via power-to-methane processes [137]. Synergy potentials between the gas and electricity sectors are explored for various renewable gas production pathways under energy efficiency and sufficiency scenarios, using the *Open Energy Modelling Framework* (oemef), operational modelling, and exergy-based optimization [147,148]. Broader European potentials for valorizing biogenic and fossil CO₂ are assessed [149], building on detailed, spreadsheet-based carbon management strategies developed for Austria [140,141].

Pathways for decarbonizing the Austrian and European iron and steel sectors are informed by a combination of qualitative stakeholder engagement and scenario development using the computable general equilibrium (CGE) model *WEGDYN* [150,152]. Life cycle assessment (LCA) methods are also applied to estimate national integration potentials between thermal and material waste recycling and industrial sectors such as cement and paper [151].

We assess the MRL for integrated energy system and industry transformation modelling in Austria as relatively low. Only a limited number of research groups are publishing on systemic industrial decarbonization, and many of these efforts are recent and rely on spreadsheet-based methods rather than established modelling frameworks. Data availability and validation remain significant challenges, as industries are often reluctant to disclose information that could compromise their competitive advantage—particularly regarding energy efficiency and primary energy substitution.

Nonetheless, there is a clear opportunity to strengthen integration by linking industrial transformation models with established frameworks for industrial waste heat utilization in district heating and cooling systems (see Section 3.2.2). Such cross-sectoral integration could enhance both the strategic and operational readiness of Austria's energy system modelling landscape.

3.2.7. Multi-sector coupling – energy system and materials

The development and deployment of energy infrastructure, including photovoltaic and wind power plants, networks, batteries, buildings, insulation materials, and other energy-related components—require substantial energy inputs across their life cycles. These inputs, often referred to as *grey energy* [186], are increasingly considered in the context of Circular Economy discussions and material flow modelling.

Representative Austrian research groups working at the intersection of energy systems and material flows include BOKU SEC [154–164], TU Wien IWR [165–177], Uni Graz ITE [178–186], and WU Wien [187–189]. Among the modelling approaches used, Computable General Equilibrium (CGE) and Input-Output (IO) models offer the highest levels of spatial and sectoral aggregation. Traditionally applied to assess macroeconomic effects based on monetary flows, these models are also capable of estimating economy-wide energy and material balances.

The multi-regional input-output model *EXIOBASE3* [159] is widely used for material flow accounting, not only for industrial sectors but also for the broader socioeconomic metabolism of the global economy [157]. It has been applied to assess global mobility infrastructure stocks [160], to explore the relationship between infrastructure density and well-being [161], and to compare these findings to the material footprint of personal mobility in Vienna [162]. In the context of electricity infrastructure, *EXIOBASE3* has been used to create global inventories of material stocks [163] and to conduct scenario modelling of future

⁸ EEGas project - Analysis of energy communities as enablers of system integration of renewable gases, coordinated by AIT. Online: <https://projekte.ffg.at/projekt/4805451>, accessed 25.06.2025.

material requirements [164]. When combined with the physical multi-regional input-output model *FABIO*, it also supports modelling of energy-agriculture linkages, highlighting imbalances in energy return on energy investment [187].

Circular Economy principles are explored through various modelling approaches. For example, the statistical entropy method has been applied to European building stocks to relate material concentration, emissions, and energy consumption [169], and to develop sustainability indicators for Austria's construction and demolition waste management strategies [172]. Bespoke models assess both embodied and operational impacts to derive renovation and construction quotas for Austria's building sector [178,232]. Building life cycle assessments (LCAs) have been conducted for all European countries using regionalized inventories [180], and prospective LCAs have been developed for the Austrian building stock to evaluate the impact of sufficiency measures [179]. Recent studies increasingly focus on carbon footprint assessments and the CO₂ storage potential of biobased building materials [183–185]. The *Scalable, high-definition Life Cycle Engineering (SLiCE)* model represents the first formal building data model to integrate grey energy into its algorithm, enabling dynamic impact assessments and systematic hotspot analyses of building construction and operation [186].

We assess the MRL for integrating material flows, Circular Economy principles, and energy system modelling in Austria as relatively low. This aligns with the international modelling landscape, where similar gaps have been identified by Nikas et al. [8]. While Austrian research groups have made significant progress using CGE and IO models to represent the entire economy and various material flows, these models typically operate at low spatial and temporal resolution. As a result, they offer limited insights into the flexibility potential that could be unlocked through multi-sector coupling.

Nonetheless, the integration of CO₂ management strategies, including carbon capture and storage, biogenic carbon sequestration in wood-based construction, and the role of traditional sectors such as waste incineration, highlights the growing need to better understand the interdependencies between energy and material systems. Advancing the MRL in this area will require bridging the gap between macroeconomic modelling and operational energy system analysis.

3.2.8. Hybrid energy systems – integrating bioenergy

Rapid electrification across all sectors is essential for achieving Austria's climate targets. However, bioenergy will continue to play a critical role during the transition and beyond, particularly in industrial process heat, residential heating, and hard-to-abate sectors such as aviation and shipping. Austria currently leads an international collaboration focused on the versatile system integration and flexibilization potential of commercially available solid, liquid, and gaseous bioenergy technologies [12,233,234].

Representative Austrian research groups in bioenergy system modelling include IIASA BNR [190–207] and BEST [208–215]. Despite this, modelling capacities that address the full versatility of bioenergy remain limited. No group currently simulates the dynamic interactions between renewable electricity and bioenergy, or with other energy vectors such as hydrogen.

The *Global Biosphere Management Model (GLOBIOM)* simulates annual biomass supply based on global agriculture, forestry, and bioenergy land-use databases. It supports scenario development for lignocellulosic energy crops [196], natural forest carbon potentials [203], and socio-economic aspects of agriculture and forestry [204,205], albeit at low spatial and temporal resolution. Recently, GLOBIOM was included in the first comparative study of global biomass supply models [200].

On the operational side, the *BeWhere* model—a spatially explicit, mixed-integer linear programming (MILP) tool—is used for LCA and life cycle costing (LCC) of biobased plastic production [206], and for evaluating the rollout of palm oil-based biorefineries in Indonesia [194]. *BeWhere* has also been applied to assess fuel switching to bioenergy with

carbon capture and storage (CCS) in the European iron and steel industry [197].

We assess the MRL for integrating bioenergy into electrification strategies in Austria as low. This aligns with findings by Welfle et al. [4], who identify similar gaps in the international modelling community. While some models consider the diversity of bioenergy feedstocks, supply chains, and conversion technologies, we have not identified any model-based publications that explicitly address the flexibilization potential or broader system integration impacts of hybrid energy systems combining high shares of intermittent renewable electricity with flexible bioenergy.

3.2.9. Food-water-energy nexus

Hydropower and bioenergy modelling reveal complex interdependencies between energy, water, and food systems. Hydropower storage capacities can have both beneficial and adverse effects on agricultural irrigation, while sourcing primary products and residues from agriculture and forestry for bioenergy can influence the availability of water, food, and materials—either positively or negatively.

To the best of the authors' knowledge, only IIASA currently hosts modelling capacities in Austria that explicitly address the food-water-energy nexus [216–226]. The *GLOBIOM* model is linked with other large-scale optimization frameworks to derive integrated management strategies for the *Food, Water, and Energy Security Nexus* [216–218]. The global energy system optimization model *MESSAGE* has been used to assess the impact of energy storage on energy and water security in Central Asia [219]. When coupled with the multi-regional input-output model *EXIOBASE*, *MESSAGE* enables analysis of macroeconomic effects, emerging consumption patterns, and upstream/downstream supply chains related to energy technologies [220].

Further integration is achieved by coupling *MESSAGE* with the CGE model *AIM/Hub*, allowing for comparative analysis with stand-alone model versions [221]. *MESSAGE* and *GLOBIOM* are also linked via a dedicated nexus module to explore interactions between population growth, economic development, energy, land, and water resources [222]. This model combination is soft-linked to the detailed global power system model *PLEXOS-World* [223]. Recent reviews underscore IIASA's ambition to develop leading modelling capacities for the *climate, land, energy, and water nexus* [224,225], and a new tool—*Nexus Solution Tool (NEST)*—has been introduced to optimize multi-scale transformations across energy, water, and land systems [226].

Despite the sophistication of these internationally recognized modelling suites, we estimate the MRL for food-water-energy nexus modelling in Austria to be relatively low. The integration of these domains is constrained by the large number of decision variables and the limited number of parameters that can be hard linked across models. As a result, spatial and temporal resolutions are typically coarse, which limits the ability to capture short-term dynamics and localized impacts.

Nevertheless, these models do simulate certain integration dynamics, such as resource competition and trade-offs between land use for food versus energy crops, albeit typically at a relatively coarse temporal resolution, without accounting for temporal flexibility. The emphasis on trade-offs often overshadows the exploration of synergies, particularly among integrated food, materials, and energy systems, such as the bioeconomy [7]. As discussed in the introduction, IAMs have traditionally linked climate and energy scenarios through CO₂ emissions as the primary coupling parameter. Recent advancements, as outlined in this section, have expanded the set of linked parameters. However, the explicit assessment of deliberate sectoral integration to harness the benefits of cohesive policy planning does not yet appear to be a central focus of IAMs.

3.3. Austrian disaster risk management – a missing link for temporal integration

In addition to the system integration aspects discussed in Section 3.3,

we use our literature dataset and Austrian case study to estimate the MRL for integrating extreme events and structural breaks into energy system models:

Currently, only a few Austrian research groups are actively publishing on the integration of extreme events into energy system models. Representative groups include BOKU INWE [97,235–239] and IIASA ECE [240–247]. For instance, the *Medea* power system model—a technology-rich, partial-equilibrium model of the Austro-German electricity and district heating markets—has been applied to wind and PV expansion scenarios in Austria and adapted for Brazil [97,238,239]. This model integrates strategic scenario planning with the simulation of extreme freezing events, such as those that triggered the 2021 Texas rolling blackouts [236,237], and incorporates risk mitigation strategies using Modern Portfolio Theory [95].

The *MESSAGE* model has been used to simulate the impacts of pandemics, wars, and global energy transitions across the energy system, including upstream fuel supply, renewable energy investments, energy service demand, and implications for energy equity [244]. Adaptive capacities are quantified within the Shared Socioeconomic Pathways (SSP) framework [245]. These methods have also been applied to assess climate-induced urban heat stress [246] and the need for equitable access to cooling technologies [247].

We estimate the MRL for integrating risks and extreme events, whether induced by Earth system dynamics or human system disruptions, into Austrian energy system models to be relatively low. Table 3 categorizes different risk sources and summarizes Austria's current modelling capacities and their respective focus areas. This breakdown helps identify which types of extreme events are currently considered and highlights non-energy modelling capacities that could serve as valuable links for expanding temporal integration in energy system models.

Austria hosts an internationally recognized collaboration network in the field of Disaster Risk Management (DRM), with a strong focus on flood risk and mountain resilience. Key contributors include BOKU, IIASA, the University of Salzburg, and Geosphere Austria [248–282]. Quantitative DRM methods encompass spatiotemporal flood vulnerability assessments, including the mapping of homogeneous regions, hotspots, and typologies [263,264], and the development of risk frameworks for integration into Austria's National Meteorological and Hydrological Services [265]. A national event-based loss and damage database has also been established [266].

Recent approaches combine data-driven and participatory methods, such as *Impact Chain-based climate risk and vulnerability assessments* [267], pandemic and epidemic risk management at the municipal level [268], and evaluations of non-economic flood-related losses [269]. These efforts also address Austria's intolerable risks from climate change and the limits of adaptation [270].

Formalized quantitative risk modelling focuses on Austria's flood risk management apparatus [271] employing supply-side IO models to estimate indirect economic impacts [272], and combining CGE and ABM approaches for multi-model flood event analysis [273]. These insights are empirically tested within participatory governance frameworks [274], enabling multi-hazard and multi-risk assessments that explore the interconnectedness of different risk types [275].

Advanced concepts such as risk layering are used to differentiate, prioritize, and orchestrate risk management options for both incremental and transformative change [276,277]. Firm-level data and tools from network analysis and system dynamics are proposed to quantify systemic risks, identify vulnerable interconnections in supply chains, and design mitigation strategies [278]. Integrative frameworks are being developed to address individual risks that may trigger systemic or network-level failures [279], including simultaneous disruptions in food supply chains [280], fiscal risks such as the inability of governments to finance disaster losses [281], and existential risks and global reasons for concern [282].

Energy system modelling groups in Austria could benefit

significantly from engaging with this well-established DRM community, particularly in relation to extreme events originating in the hydrosphere and geosphere. Other risk domains are also being modelled in Austria, including forest fire risks by IIASA BNR [283–288], and supply chain risks by BOKU [289–293] and CSH [294–298].

However, our literature dataset reveals a lack of modelling efforts addressing other critical risk domains. These include biosphere-related risks (e.g., pests, biodiversity collapse), technosphere risks (e.g., supply chain blockages, accidents, storage fires, congestion), cybersphere threats (e.g., cyberattacks, communication failures), and econosphere disruptions (e.g., market crashes, currency instability, border closures, sanctions). Many of these events can be expected to be documented in relatively robust historical datasets, often more complete than those available for extremes induced by global warming, and should therefore be prioritized in future energy system modelling efforts.

Integrating these diverse risk sources into energy system models would not only enhance temporal integration but also improve system resilience and preparedness. Advancing the MRL in this area requires a deliberate effort to bridge the gap between energy modelling and the broader DRM landscape, leveraging existing expertise and data to simulate and optimize responses to both gradual and abrupt disruptions.

3.4. Uncertainties in energy system models: from trends, to fluctuations, to extremes

Historically, energy system models have focused on comparing scenarios of uncertain trend developments, initially centered on political and socio-economic uncertainties and later incorporating uncertain climate trajectories (see Introduction). More recently, attention has shifted toward expanding strategic models with operational components to address the intermittent nature of photovoltaic and wind power generation, and to explore how system integration can provide the flexibility needed to balance these fluctuations (see Section 3.3). In Section 3.4, we further highlighted the emerging focus on modelling extreme events. This evolution is summarized in Table 4, which opens the discussion on a broader trajectory of energy system modelling.

Most modelling approaches handle uncertainties by analyzing sensitivities across ensembles of deterministic scenarios, which tends to underestimate the relevance of probabilistic effects [299]. While scenario analysis may suffice for capturing long-term trend uncertainties, mitigated through strategic flexibility, it often fails to adequately represent short- and medium-term variabilities, which require operational flexibility [300].

To better capture the effects of flexibility, especially for short-term fluctuations, energy system models are increasingly incorporating probabilistic and operational methods. These include stylized temporal integration using high-resolution time series, stochastic programming, and semi-dynamic balancing approaches based on typical days [301]. The next frontier involves integrating extreme events into energy system models, and how transformation pathways can be designed flexible enough to be reliable under a large set of unforeseen circumstances. However, energy system models simulating the effects of extreme events are still a niche area both in Austria and globally, as noted by McCollum et al. [302]. Some IAMC authors have even advocated for the inclusion of currently neglected catastrophic climate change scenarios in future IPCC assessments [303].

Risk-based methods such as real options analysis, stochastic optimization, and mean-variance portfolio theory aim to bridge strategic and event-based modelling. However, these approaches remain underutilized in energy system modelling [304]. Most reviews agree that the proper representation of uncertainty remains one of the field's central challenges [30,35,305–307]. Moreover, the push for higher spatial and sectoral integration multiplies the number of decision variables, and with them, the associated uncertainties.

Table 4 offers a simplified overview of the types of uncertainties relevant to energy system modelling. Kirchner et al. [308] provide a

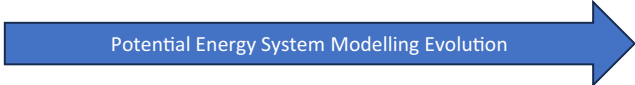
Table 3

Different risk sources and Austria's risk modelling capacities and their risk focus. Source: own evaluation.

Risk Sources	Modelled risks	Groups and references
Earth system risk sources and risks		
 Atmosphere	Extreme weather impact on electricity supply	BOKU INWE [97, 235-239]
	Heat stress and residential cooling	IIASA ECE [240-247]
 Hydro/Cryosphere	Flood risks and alpine risk management but no link to energy system modelling yet	BOKU ILAP, BOKU IAN, Uni Salzburg, IIASA POPJUS, IIASA ASA, Geosphere Austria [248-282]
 Geosphere		
 Biosphere	Forest fires modelling, but no link to energy system yet	IIASA BNR [283-288]
Human system risk sources and risks		
 Sociosphere	Wars, pandemics, few publications on effects on energy system	IIASA ECE [244, 245]
 Technosphere	Supply chain risks but not for the energy system yet	BOKU PWL [289-293]
	Supply chain risk cascades	CSH [294-298]
 Ecosphere	Market crash, currency risks, border risks	No literature identified
 Cybersphere	Cyber-attacks, failing Internet and Communication technologies	No literature identified

Table 4

Modelling readiness levels (MRL) for energy system models capturing different types of uncertainties. Source: Own assessment.

	Trends	Variabilities	Extremes
			
Earth system <i>Considered uncertainties in ESMs</i>	High MRL <i>on global warming</i>	Medium MRL <i>on weather seasonality and day-nighttime</i>	Low but growing MRL <i>on climate extremes</i>
Human system <i>Considered uncertainties in ESMs</i>	High MRL <i>on socio-economic trends</i>	Medium MRL <i>on costs and prices, on trade</i>	Lowest MRL <i>on accidents, market crashes, wars, cyber-threats</i>
			

more nuanced classification, distinguishing between statistical, scenario-based, qualitative, deliberately ignored, and consciously recognized but unaddressed uncertainties. These arise from various sources, including system boundaries and resolution, input data, system drivers, parameter calibration, model structure, hardware and software limitations, outcome extrapolation, and the translation of results into decision support. In contrast, the uncertainty types addressed in Table 4 are intended to help modellers quickly reflect on how their models incorporate temporal integration and which types of uncertainties could

be represented to simulate the impacts of system integration more effectively.

3.5. System Integration Impact Assessment (SIIA) – embracing uncertainties

We advocate for energy system modellers, funding agencies, and policymakers to adopt a more deliberate and structured approach to assessing the impacts of system integration. The Austrian case study

reveals significant disparities in the modelling of different system integration aspects. While policy documents frequently claim to be “integrated,” the modelling frameworks underpinning them often are not. This disconnect is evident in the *Österreichischer Netzinfrastukturanplan (ÖNIP)*, which addresses electricity and gas grid integration, and similarly in Austria’s *Integrated National Energy and Climate Plan (NECP)* [309], where system integration and climate impacts are scarcely reflected in the underlying energy system models.

Truly integrated planning, such as that envisioned in the ÖNIP and NECP, should be grounded in models capable of capturing interactions and synergies across networks, production and consumption systems, and climate-related objectives. However, the current MRL of modelling frameworks remains limited in their ability to simulate the value proposition of integrated planning by explicitly representing these interactions, synergies, trade-offs, and threats.

The Austrian case study underscores the urgent need for the energy system modelling community to reflect on the meaning of “integration” and to develop models that can endogenously capture its effects. We propose the concept of *System Integration Impact Assessment (SIIA)*, which builds on the long-standing tradition of technology assessment in the United States and German [310,311]. SIIA should aim to objectively evaluate both the benefits and risks of integrated versus separate systems and solutions.

Flexibility is a key emergent property of integrated systems. We define flexibility as the ability to shift (energy) resources through time, space, between sectors, and options. This ability can be used to balance shortages with surpluses, thereby simultaneously increasing resource efficiency and system reliability [7,128,130,312–314]. However, this ability can also be misused by shifting resources from regions, times, or sectors that need them to areas where there is already a surplus, resulting in systemic risks, including the potential for cascading failures [273,315,316]. Therefore, SIIA must place equal emphasis on supporting the design and operation of combined infrastructures, technologies, and sectors by enhancing and safeguarding:

- (a) overall resource efficiency for a large variety of different types of resources, and
- (b) system reliability in the face of uncertain trends, variabilities, and extreme events.

We estimate the current MRL for SIIA in Austria to be relatively low, though promising developments can be highlighted within both the energy system modelling and disaster risk management communities. The growing focus on temporal integration of intermittent renewables and complementary flexibility options presents a timely opportunity to explore the value proposition of system integration beyond the electricity sector and anticipate how systems can be designed to embrace not only the uncertainty of renewable intermittency but also more severe disruptions arising from natural or anthropogenic events.

3.6. Limitations

A key limitation of this study lies in its geographically constrained scope, focusing exclusively on main authors with an Austrian affiliation. While this allowed for a quasi-comprehensive mapping of national modelling capacities, the methodology developed and tested here should be applied to larger datasets, additional countries, and broader literature corpora, including sources beyond Scopus and OpenAlex, and potentially in languages other than English. Despite this limitation, the core insights derived from the Austrian case study are expected to hold relevance for energy system modellers globally, particularly in highlighting the uneven modelling readiness across system integration aspects.

International collaboration is essential for the Austrian energy system modelling community, as evidenced by the fact that most publications in the literature database underlying this manuscript include at

least one co-author affiliated with a non-Austrian institution. Germany, the United States, Great Britain, Switzerland, the Netherlands, Italy, Sweden and Norway are the most relevant countries for the co-authoring with Austrian affiliations. The international co-authorship network is illustrated in a previous version of this publication (accessible online⁹). However, it was beyond the scope of this study to assess the extent to which international collaboration addresses the methodological gaps identified for advancing System Integration Impact Assessment.

Another limitation of this study lies in the limited in-depth discussion of modelling approaches that could integrate strategic, operational, and risk-based modelling approaches, particularly in the context of extreme events. Future work should demonstrate how these methods can be combined to better capture the synergies, trade-offs, and threats associated with temporal, sectoral, and spatial integration. Of particular interest are positive and negative tipping points, which may lead to structural breaks that are either devastating for specific sectors and societies or desperately needed and transformative in ways that significantly enhance and democratize social welfare. The ability to model such dynamics could help overcome path dependencies and support the design of robust, sustainable pathways in the face of polycrises. However, this capability also raises ethical considerations, as it could be misused to identify vulnerabilities and intentionally destabilize systems. As such, advancing this line of research must be accompanied by a critical reflection on dual-use risks and the governance of modelling practices.

4. Conclusions and recommendations

Policy decision making is becoming increasingly complex. On the one hand, the climate and biodiversity crises, combined with the interconnectedness of the global population governed across multiple levels, amplify the uncertainties that must be considered to ensure robust decisions. On the other hand, humanity actively pursues complexifications such as in the organization of energy resources, to induce flexibility and buffer the effects of uncertainty. System integration enables us to embrace such uncertainties, which may stand in contrast to uncertainty reduction strategies that rely on simplifying systems and limiting flexibility.

System Integration Impact Assessment (SIIA) should support decision-makers with modelling-backed strategies to explain emergence, and to amplify beneficial and mitigate detrimental impacts of planned complexification. In doing so, SIIA can help counteract the compartmentalization of problem-solving capacities, whether in the form of academic silos, separately administered and planned sectors, or even tendencies to retreat from international collaboration. SIIA can strengthen the narrative for integration by providing evidence and know-how on its societal value, while also identifying concrete threats emerging from integrated systems and how to address them.

We present a case study of Austrian-hosted energy system models embedded in an international context. Many of these models currently focus on capturing the effects of intermittent renewables and how they can be balanced through flexibility options enabled by temporal, spatial, and sectoral integration. We find varying Modelling Readiness Levels (MRLs) across different integration aspects and discuss opportunities and barriers for MRL improvements, including the interdisciplinary translation of methods.

Regarding sector integration, electricity and heating systems emerge as promising nuclei for extending integration to lower-MRL sectors such as mobility, industry, and bioenergy. Austria hosts established models with spatial representations of electricity and heating networks, which could serve as steppingstones for improving spatial integration. To capture the effects of different prosumer topologies, multi-level governance, and energy communities—an emerging modelling theme in some

⁹ <https://zenodo.org/records/15276174> (accessed 2025.11.22).

groups—energy system models will need to incorporate multiple spatial resolution layers. Furthermore, Austria hosts internationally renowned Integrated Assessment Models (IAMs), which could facilitate the assessment of integration impacts beyond trade-offs, including a more pronounced focus on synergies between entangled energy, food, materials, and water sectors.

Most notably, we observe a growing awareness of different types of uncertainties, which could boost the temporal integration of energy system models. Many modelling groups are working to implement operational considerations into long-term scenario models to better capture the stochasticity of intermittent renewables. We understand this development as an opening window of opportunity to also model shocks and structural breaks. To advance temporal integration, energy system models may need to adapt methods, datasets, and tools from other disciplines, such as process engineering for operational aspects and disaster risk management for extreme events. These perspectives could shed new light on the value of storage, interconnectivity, and systemic resilience.

We recommend structurally planning for SIIA by recognizing the different MRLs of various system integration challenges and by supporting especially low-MRL topics such as bioenergy and bioeconomy modelling, as well as rapidly advancing areas like energy community modelling. The parallel development and proliferation of selected system integration aspects proves useful for rapid prototyping of models and science-policy interfaces. However, the combination of different system integration aspects will only be as strong as its weakest link.

With this publication, we provide a first assessment of the MRL of Austrian SIIA approaches. Together with the openly shared and frequently downloaded researcher and research group dataset, this work should serve as a basis for establishing collaborations that can advance SIIA in Austria and internationally. Future conceptual work on SIIA must better highlight not only the synergies but also the threats of system integration, and how knowledge about the flexibility and reliability of coupled sectors could potentially be misused to trigger cascading vulnerabilities and system collapse. This dual-use aspect of SIIA deserves careful attention.

CRedit authorship contribution statement

Fabian Schipfer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding

Annex

Table 5

List of Austria-based research groups relevant to and abbreviations used in this review. For more details and group and researcher-specific bibliometric evaluations, see the spreadsheets in the Supplementary materials.

Type	Abbreviation	Affiliation	Faculty/Research Programme/Chairs
Institute	AEA	Austrian Energy Agency	Energy Economics
Institute	AIT DRC	Austrian Institute of Technology GmbH	Competence Unit Digital Resilient Cities
Institute	AIT IES	Austrian Institute of Technology GmbH	Competence Unit Integrated Energy Systems
Institute	AIT PRGS	Austrian Institute of Technology GmbH	Power and Renewable Gas Systems
Institute	AIT SCT	Austrian Institute of Technology GmbH	Competence Unit Security and Communication Technologies
Institute	ASCI	Supply Chain Intelligence Institute Austria	Area 2 Digital Methods and Solutions
Institute	BEST Area 2.2	Bioenergy and Sustainable Technologies GmbH	Area 3 Sustainable Supply and Value Cycles
Institute	BEST Area 3	Bioenergy and Sustainable Technologies GmbH	Department of Landscape, Spatial and Infrastructure Sciences
University	Boku Geo	University of Natural Resources and Life Sciences	Department of Civil Engineering and Natural Hazards
University	BOKU IAN	University of Natural Resources and Life Sciences	Department of Agrobiotechnology
University	BOKU IEB	University of Natural Resources and Life Sciences	Department of Landscape, Spatial and Infrastructure Sciences
University	Boku ILAP	University of Natural Resources and Life Sciences	Department of Economics and Social Sciences
University	BOKU INWE	University of Natural Resources and Life Sciences	

(continued on next page)

acquisition, Formal analysis, Data curation, Conceptualization. **Michael Harasek:** Validation, Resources, Project administration. **Shubham Tiwari:** Writing – original draft, Investigation, Conceptualization. **Florian Kraxner:** Validation, Resources, Conceptualization. **Johannes Schmidt:** Validation, Resources, Conceptualization. **Sebastian Wehrle:** Writing – original draft, Formal analysis, Conceptualization. **Neda Asasian Kolur:** Validation. **Daniela Thrän:** Validation, Conceptualization. **Danial Esmaeili Aliabadi:** Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Hanna Breunig:** Validation, Resources, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fabian Schipfer reports financial support was provided by Austrian Ministry for Transport, Innovation and Technology (BMK). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the three independent reviewers for their valuable comments as well as the editor for their efforts. The research behind this paper was financed by the Austrian Ministry for Transport, Innovation and Technology (BMK) under grant number FO999905734 and the title ‘Integrative energy infrastructure planning tool for cross-sector resilience and flexibility concepts’ and with the project homepage <https://projekte.ffg.at/projekt/4875820>. The authors acknowledge the TU Wien Library for financial support through its Open Access Funding Programme. We also thank the IEA Bioenergy TCP Task44 and its members for the discussions on flexibility and system integration that coined this paper (<https://task44.ieabioenergy.com/>). Special thanks go to Prof. Anna Krook-Riekola and Prof. Amro Farid from the IEAs Energy Technology Systems Analysis Programme (ETSAP) for the valuable discussions on the opportunities and challenges of modelling system integration and flexibility. English grammar, syntax and scientific writing style were furthermore manifold upgraded by the Grammarly software, and Microsoft CoPilot.

Table 5 (continued)

Type	Abbreviation	Affiliation	Faculty/Research Programme/Chairs
University	BOKU PWL	University of Natural Resources and Life Sciences	Department of Economics and Social Sciences
University	BOKU SEC	University of Natural Resources and Life Sciences	Department of Economics and Social Sciences
University	CEU	Central European University	Department of Environmental Sciences and Policy
Institute	CSH	Complexity Science Hub	Metabolism of Societies
University	Donau Uni	University for Continuing Education Krems	Department for Integrated Sensor Systems
Institute	ethink	ethink Energy Research	
University	FHV	Vorarlberg University of Applied Sciences	Energy Research Centre
Institute	Geosphere Austria	Geosphere Austria - Bundesanstalt für Geologie, Geophysik, Klimatologie und Meteorologie	Risk Lab
Institute	IIASA ASA	International Institute of Applied Systems Analysis	Advancing Systems Analysis
Institute	IIASA BNR	International Institute of Applied Systems Analysis	Biodiversity and Natural Resources
Institute	IIASA BNR/AFE	International Institute of Applied Systems Analysis	Biodiversity and Natural Resources
Institute	IIASA ECE	International Institute of Applied Systems Analysis	Energy, Climate, and Environment
Institute	IIASA POPJUS	International Institute of Applied Systems Analysis	Population and Just Societies
University	JKU	Johannes Kepler Universität Linz	Energieinstitut
Institute	Joanneum LIFE	Joanneum Research Forschungsgesellschaft mbH	Institute for Climate, Energy Systems and Society
University	Montan Uni ENT	Montan Universität Leoben	Chair of Energy Network Technology
University	TU Graz IEE	Graz University of Technology	Faculty of Electrical and Information Engineering
University	TU Graz IRT	Graz University of Technology	Faculty of Electrical and Information Engineering
University	TU Graz IWT	Graz University of Technology	Faculty of Mechanical Engineering and Economic Sciences
University	TU Wien BPI	Technische Universität Wien	Faculty of Architecture and Planning
University	TU Wien EEG	Technische Universität Wien	Faculty of Electrical Engineering and Information Technology
University	TU Wien ICEBE	Technische Universität Wien	Faculty of Technical Chemistry
University	TU Wien ICT	Technische Universität Wien	Faculty of Electrical Engineering and Information Technology
University	TU Wien IET	Technische Universität Wien	Faculty of Mechanical and Industrial Engineering
University	TU Wien IWR	Technische Universität Wien	Faculty of Civil- and Environmental Engineering
University	TU Wien NES	Technische Universität Wien	Faculty of Electrical Engineering and Information Technology
University	TU Wien Transport	Technische Universität Wien	Faculty of Civil- and Environmental Engineering
University	TU Wien WRM	Technische Universität Wien	Faculty of Civil- and Environmental Engineering
University	Uni Graz BANDAS	University of Graz	Facultät für Sozial- und Wirtschaftswissenschaften
University	Uni Graz Geo	University of Graz	Faculty of Environmental, Regional and Educational Science
University	Uni Graz ITE	University of Graz	Faculty of Architecture
University	Uni Innsbruck	University of Innsbruck	
University	Uni Salzburg	University of Salzburg	Department of Geoinformatics Z_GIS
University	Uni Wien BDA	Universität Wien	Faculty of Business, Economics and Statistics
University	Uni Wien Geo	Universität Wien	Faculty of Earth Sciences, Geography and Astronomy
University	Wegener Center	University of Graz	Wegener Center for Climate and Global Change
Institute	WIFO	Austrian Institute of Economic Research	
University	WU Wien ITL	Wirtschaftsuniversität Wien	Department of Global Business and Trade

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.erss.2025.104505>.

Data availability

all attached

References

- [1] P.N. Edwards, History of climate modeling, *WIREs Clim. Change* 2 (1) (2010) 128–139, <https://doi.org/10.1002/wcc.95>.
- [2] K.C. Hoffman, Large-scale energy modeling - perspectives and policy applications, *IFAC Proceedings Volumes* 14 (2) (1981) 3189–3197, [https://doi.org/10.1016/S1474-6670\(17\)63944-2](https://doi.org/10.1016/S1474-6670(17)63944-2).
- [3] A. Chiodi, G. Giannakidis, M. Labriet, B. Ó Gallachóir, G. Tosato, Introduction: energy systems modelling for decision-making, in: *Lecture Notes in Energy*, Springer International Publishing, 2015.
- [4] A. Welfle, P. Thornley, M. Röder, A review of the role of bioenergy modelling in renewable energy research & policy development, *Biomass Bioenergy* 136 (2020), <https://doi.org/10.1016/j.biombioe.2020.105542>.
- [5] A. Pyka, G. Cardellini, H. van Meijl, P.J. Verkerk, Modelling the bioeconomy: emerging approaches to address policy needs, *J. Clean. Prod.* 330 (2022), <https://doi.org/10.1016/j.jclepro.2021.129801>.
- [6] C.J. Querton, O. Tlili, L. Welder, C. Mansilla, H. Blanco, H. Heinrichs, J. Leaver, N.J. Samsatli, P. Lucchese, M. Robinius, S. Samsatli, The curious case of the conflicting roles of hydrogen in global energy scenarios, *Sustainable Energy Fuels* 4 (1) (2020) 80–95, <https://doi.org/10.1039/c9se00833k>.
- [7] F. Schipfer, P. Burli, U. Fritsche, C. Hennig, F. Stricker, M. Wirth, S. Proskurina, S. Serna-Loaiza, The circular bioeconomy: a driver for system integration, *Energy Sustain. Soc.* 14 (1) (2024), <https://doi.org/10.1186/s13705-024-00461-4>.
- [8] A. Nikas, G. Xexakis, K. Koasidis, J. Acosta-Fernández, I. Arto, A. Calzadilla, T. Domenech, A. Gambhir, S. Giljum, M. Gonzalez-Eguino, A. Herbst, O. Ivanova, M.A.E. van Sluiseveld, D.-J. Van De Ven, A. Karamaneas, H. Doukas, Coupling circularity performance and climate action: from disciplinary silos to transdisciplinary modelling science, *Sustainable Prod. Consumption* 30 (2022) 269–277, <https://doi.org/10.1016/j.spc.2021.12.011>.
- [9] S.-M. Horvath, M.M. Muhr, M. Kirchner, W. Toth, V. Germann, L. Hundscheid, H. Vacik, M. Scherz, H. Kreiner, F. Fehr, F. Borgwardt, A. Günnemann, B. Becsi, A. Schneeberger, G. Gratzner, Handling a complex agenda: a review and assessment of methods to analyse SDG entity interactions, *Environ. Sci. Policy* 131 (2022) 160–176, <https://doi.org/10.1016/j.envsci.2022.01.021>.
- [10] M. O'Malley, B. Kroposki, et al., Energy Systems Integration: Defining and Describing the Value Proposition, NREL, 2016, <https://doi.org/10.2172/1257674>.
- [11] M. O'Malley, B. Kroposki, Unlocking flexibility: energy systems integration [guest editorial], *IEEE Power and Energy Magazine* 15 (1) (2017) 10–14, <https://doi.org/10.1109/mpe.2016.2629703>.
- [12] F. Schipfer, E. Mäki, U. Schmieder, N. Lange, T. Schildhauer, C. Hennig, D. Thrän, Status of and expectations for flexible bioenergy to support resource efficiency and to accelerate the energy transition, *Renew. Sustain. Energy Rev.* 158 (2022), <https://doi.org/10.1016/j.rser.2022.112094>.

- [13] B.P. Koirala, E. Koliou, J. Friege, R.A. Hakvoort, P.M. Herder, Energetic communities for community energy: a review of key issues and trends shaping integrated community energy systems, *Renew. Sustain. Energy Rev.* 56 (2016) 722–744, <https://doi.org/10.1016/j.rser.2015.11.080>.
- [14] E. O'Dwyer, I. Pan, S. Acha, N. Shah, Smart energy systems for sustainable smart cities: current developments, trends and future directions, *Appl. Energy* 237 (2019) 581–597, <https://doi.org/10.1016/j.apenergy.2019.01.024>.
- [15] G. Chicco, S. Riaz, A. Mazza, P. Mancarella, Flexibility from distributed multienergy systems, *Proc. IEEE* 108 (9) (2020) 1496–1517, <https://doi.org/10.1109/jproc.2020.2986378>.
- [16] Ş. Kılış, G. Kraljčić, N. Duić, M.A. Rosen, M.d.A. Al-Nimr, Advances in integration of energy, water and environment systems towards climate neutrality for sustainable development, *Energ. Convers. Manage.* 225 (2020), <https://doi.org/10.1016/j.enconman.2020.113410>.
- [17] G. Airò Farulla, M. Cellura, F. Guarino, M. Ferraro, A review of thermochemical energy storage systems for power grid support, *Appl. Sci.* 10 (9) (2020), <https://doi.org/10.3390/app10093142>.
- [18] M. Hammerschmid, D.C. Rosenfeld, A. Bartik, F. Benedikt, J. Fuchs, S. Müller, Methodology for the development of virtual representations within the process development framework of energy plants: from digital model to digital predictive twin—a review, *Energies* 16 (6) (2023), <https://doi.org/10.3390/en16062641>.
- [19] eurostat, eurostat newsrelease, in: First Population Estimates - EU Population Up to Over 513 Million on 1 January 2019, 2019.
- [20] E. Raheli, Q. Wu, M. Zhang, C. Wen, Optimal coordinated operation of integrated natural gas and electric power systems: a review of modeling and solution methods, *Renew. Sustain. Energy Rev.* 145 (2021), <https://doi.org/10.1016/j.rser.2021.111134>.
- [21] X. Tian, C. An, Z. Chen, The role of clean energy in achieving decarbonization of electricity generation, transportation, and heating sectors by 2050: a meta-analysis review, *Renew. Sustain. Energy Rev.* 182 (2023), <https://doi.org/10.1016/j.rser.2023.113404>.
- [22] R. Kakodkar, G. He, C.D. Demiran, M. Arbabzadeh, S.G. Baratsas, S. Avraamidou, D. Mallapragada, I. Miller, R.C. Allen, E. Gençer, E. N. Pistikopoulos, A review of analytical and optimization methodologies for transitions in multi-scale energy systems, *Renew. Sustain. Energy Rev.* 160 (2022), <https://doi.org/10.1016/j.rser.2022.112277>.
- [23] K. Johansen, S. Werner, Something is sustainable in the state of Denmark: a review of the Danish district heating sector, *Renew. Sustain. Energy Rev.* 158 (2022), <https://doi.org/10.1016/j.rser.2022.112117>.
- [24] J. Jiang, B. Hu, R.Z. Wang, N. Deng, F. Cao, C.-C. Wang, A review and perspective on industry high-temperature heat pumps, *Renew. Sustain. Energy Rev.* 161 (2022), <https://doi.org/10.1016/j.rser.2022.112106>.
- [25] P. Diesing, G. Lopez, P. Blechinger, C. Breyer, From knowledge gaps to technological maturity: a comparative review of pathways to deep emission reduction for energy-intensive industries, *Renew. Sustain. Energy Rev.* 208 (2025), <https://doi.org/10.1016/j.rser.2024.115023>.
- [26] Y. Jin, P. Behrens, A. Tukker, L. Scherer, Water use of electricity technologies: a global meta-analysis, *Renew. Sustain. Energy Rev.* 115 (2019), <https://doi.org/10.1016/j.rser.2019.109391>.
- [27] P.D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, Review of energy system flexibility measures to enable high levels of variable renewable electricity, *Renew. Sustain. Energy Rev.* 45 (2015) 785–807, <https://doi.org/10.1016/j.rser.2015.01.057>.
- [28] M. Liu, N.H. Steven Tay, S. Bell, M. Belusko, R. Jacob, G. Will, W. Saman, F. Bruno, Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies, *Renew. Sustain. Energy Rev.* 53 (2016) 1411–1432, <https://doi.org/10.1016/j.rser.2015.09.026>.
- [29] P. Kohlhepp, H. Harb, H. Wolisz, S. Waczowicz, D. Müller, V. Hagenmeyer, Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: a review of international field studies, *Renew. Sustain. Energy Rev.* 101 (2019) 527–547, <https://doi.org/10.1016/j.rser.2018.09.045>.
- [30] P. Lopian, P. Markewitz, M. Robinus, D. Stolten, A review of current challenges and trends in energy systems modeling, *Renew. Sustain. Energy Rev.* 96 (2018) 156–166, <https://doi.org/10.1016/j.rser.2018.07.045>.
- [31] R. Martínez-Gordón, G. Morales-España, J. Sijm, A.P.C. Faaij, A review of the role of spatial resolution in energy systems modelling: lessons learned and applicability to the North Sea region, *Renew. Sustain. Energy Rev.* 141 (2021), <https://doi.org/10.1016/j.rser.2021.110857>.
- [32] A.S. Dagoumas, N.E. Koltsaklis, Review of models for integrating renewable energy in the generation expansion planning, *Appl. Energy* 242 (2019) 1573–1587, <https://doi.org/10.1016/j.apenergy.2019.03.194>.
- [33] B. Sharma, R.G. Ingalls, C.L. Jones, A. Khanchi, Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future, *Renew. Sustain. Energy Rev.* 24 (2013) 608–627, <https://doi.org/10.1016/j.rser.2013.03.049>.
- [34] L. Hofbauer, W. McDowall, S. Pye, Challenges and opportunities for energy system modelling to foster multi-level governance of energy transitions, *Renew. Sustain. Energy Rev.* 161 (2022), <https://doi.org/10.1016/j.rser.2022.112330>.
- [35] A. Krumm, D. Süßer, P. Blechinger, Modelling social aspects of the energy transition: what is the current representation of social factors in energy models? *Energy* 239 (2022) <https://doi.org/10.1016/j.energy.2021.121706>.
- [36] F. Birkelbach, D. Huber, R. Hofmann, Piecewise linear approximation for MILP leveraging piecewise convexity to improve performance, *Computers and Chemical Engineering* 183 (2024), <https://doi.org/10.1016/j.compchemeng.2024.108596>.
- [37] M. Fischer, K.W. Schenzel, R. Hofmann, Multi-stage optimization for marketing industrial flexibility, *Computer Aided Chemical Engineering* 52 (2023) 215–220, <https://doi.org/10.1016/B978-0-443-15274-0.50035-4>.
- [38] V. Halmischlager, F. Birkelbach, R. Hofmann, Optimizing the utilization of excess heat for district heating in a chipboard production plant, *Case Stud. Therm. Eng.* 25 (2021), <https://doi.org/10.1016/j.csite.2021.100900>.
- [39] V. Halmischlager, R. Hofmann, Assessing the potential of combined production and energy management in Industrial Energy Hubs – analysis of a chipboard production plant, *Energy* 226 (2021), <https://doi.org/10.1016/j.energy.2021.120415>.
- [40] D. Huber, F. Birkelbach, R. Hofmann, HENS unchained: MILP implementation of multi-stage utilities with stream splits, variable temperatures and flow capacities, *Energies* 16 (12) (2023), <https://doi.org/10.3390/en16124732>.
- [41] D. Huber, F. Birkelbach, R. Hofmann, Non-Pareto optimal solutions as enablers for versatile heat exchanger networks, *Computer Aided Chemical Engineering* 52 (2023) 113–118, <https://doi.org/10.1016/B978-0-443-15274-0.50019-6>.
- [42] D. Huber, K. Werdinig, F. Birkelbach, R. Hofmann, Highly efficient heat integration of a power-to-liquid process using MILP, in: 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2023, International Conference on Efficiency Cost Optimization Simulation and Environmental Impact of Energy Systems, 2023, pp. 1229–1239, <https://doi.org/10.52202/069564-0112>.
- [43] L. Kasper, D. Pernsteiner, A. Schirrer, S. Jakubek, R. Hofmann, Experimental characterization, parameter identification and numerical sensitivity analysis of a novel hybrid sensible/latent thermal energy storage prototype for industrial retrofit applications, *Appl. Energy* 344 (2023), <https://doi.org/10.1016/j.apenergy.2023.121300>.
- [44] S. Knöttner, B. Leitner, R. Hofmann, Impact of recent district heating developments and low-temperature excess heat integration on design of industrial energy systems: an integrated assessment method, *Energy Convers. Manage.* 263 (2022), <https://doi.org/10.1016/j.enconman.2022.115612>.
- [45] L. Prendl, K. Schenzel, R. Hofmann, Simultaneous integration of heat pumps and different thermal energy storages into a tightened multi-period MILP HENS superstructure formulation for industrial applications, *Comput. Chem. Eng.* 147 (2021), <https://doi.org/10.1016/j.compchemeng.2021.107237>.
- [46] N. Requate, T. Meyer, R. Hofmann, From wind conditions to operational strategy: optimal planning of wind turbine damage progression over its lifetime, *Wind Energy Science* 8 (11) (2023) 1727–1753, <https://doi.org/10.5194/wes-8-1727-2023>.
- [47] N. Requate, T. Meyer, R. Hofmann, Maximizing value through optimized annual selection of Pareto-optimal wind turbine operating strategies, in: A. Bianchini (Ed.), *Journal of Physics: Conference Series*, Institute of Physics, 2024, <https://doi.org/10.1088/1742-6596/2767/3/032045>.
- [48] J.A. Stampfli, B.H.Y. Ong, D.G. Olsen, B. Wellig, R. Hofmann, Multi-objective evolutionary optimization for multi-period heat exchanger network retrofit, *Energy* 281 (2023), <https://doi.org/10.1016/j.energy.2023.128175>.
- [49] C. Tubeuf, F. Birkelbach, A. Maly, R. Hofmann, Increasing the flexibility of hydropower with reinforcement learning on a digital twin platform, *Energies* 16 (4) (2023), <https://doi.org/10.3390/en16041796>.
- [50] C. Tubeuf, F. Birkelbach, A. Maly, M. Krause, R. Hofmann, Enabling reinforcement learning for flexible energy systems through transfer learning on a digital twin platform, in: 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2023, International Conference on Efficiency Cost Optimization Simulation and Environmental Impact of Energy Systems, 2023, pp. 3218–3228, <https://doi.org/10.52202/069564-0289>.
- [51] G. Zabik, F. Birkelbach, R. Hofmann, Qualitative comparison of on-site production of hydrogen and its synthesis products for steel processing industry, in: 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2023, International Conference on Efficiency Cost Optimization Simulation and Environmental Impact of Energy Systems, 2023, pp. 2514–2522, <https://doi.org/10.52202/069564-0226>.
- [52] A. Fleischmann, A. Friedl, D. Großmann, W. Schmidt, Modeling and implementing of Industrie 4.0 scenarios, in: *Communications in Computer and Information Science* 1401 CCIS, 2021, pp. 90–112, https://doi.org/10.1007/978-3-030-72696-6_4.
- [53] S. Pratschner, M. Hammerschmid, S. Müller, F. Winter, Evaluation of CO₂ sources for Power-to-Liquid plants producing Fischer-Tropsch products, *J. CO₂ Util.* 72 (2023), <https://doi.org/10.1016/j.jcou.2023.102508>.
- [54] S. Pratschner, F. Radosits, A. Ajanovic, F. Winter, Techno-economic assessment of a power-to-green methanol plant, *J. CO₂ Util.* 75 (2023), <https://doi.org/10.1016/j.jcou.2023.102563>.
- [55] E. Saracevic, F. Theuretzbacher, D. Woess, A. Friedl, A. Miltner, Economic and technical evaluation of flexible power generation scenarios for a biogas plant, *Journal of Sustainable Development of Energy, Water and Environment Systems* 8 (2) (2020) 328–343, <https://doi.org/10.13044/j.sdewes.d7.0289>.
- [56] M. Fallahnejad, L. Kranzl, R. Haas, M. Hummel, A. Müller, L. Sánchez-García, U. Persson, District heating potential in the EU-27: evaluating the impacts of heat demand reduction and market share growth, *Appl. Energy* 353 (2024), <https://doi.org/10.1016/j.apenergy.2023.122154>.
- [57] P. Manz, A. Billerbeck, A. Kök, M. Fallahnejad, T. Fleiter, L. Kranzl, S. Braungardt, W. Eichhammer, Spatial analysis of renewable and excess heat potentials for climate-neutral district heating in Europe, *Renew. Energy* 224 (2024), <https://doi.org/10.1016/j.renene.2024.120111>.

- [58] M. Fallahnejad, R. Büchele, J. Habiger, J. Hasani, M. Hummel, L. Kranzl, P. Mascherbauer, A. Müller, D. Schmidinger, B. Mayr, The economic potential of district heating under climate neutrality: the case of Austria, *Energy* 259 (2022), <https://doi.org/10.1016/j.energy.2022.124920>.
- [59] S. Pezzutto, G. Quaglini, P. Riviere, L. Kranzl, A. Novelli, A. Zambito, L. Bottecchia, E. Wilczynski, Process cooling market in Europe: assessment of the final energy consumption for the year 2016, *Sustainability (Switzerland)* 15 (4) (2023), <https://doi.org/10.3390/su15043698>.
- [60] S. Pezzutto, G. Quaglini, A. Zambito, A. Novelli, P. Riviere, L. Kranzl, E. Wilczynski, Potential evolution of the cooling market in the EU27+UK: an outlook until 2030, *Sustainability (Switzerland)* 14 (8) (2022), <https://doi.org/10.3390/su14084461>.
- [61] S. Pezzutto, P. Riviere, L. Kranzl, A. Zambito, G. Quaglini, A. Novelli, M. Hummel, L. Bottecchia, E. Wilczynski, Recent advances in district cooling diffusion in the EU27+UK: an assessment of the market, *Sustainability (Switzerland)* 14 (7) (2022), <https://doi.org/10.3390/su14074128>.
- [62] R. Kapeller, M. Bügelmayr-Blaschek, B. Herndlner, L. Kranzl, A. Müller, S. Moser, T. Natiesta, J. Reichl, R. Schwalbe, The effects of climate change-induced cooling demand on power grids, *Energy Rep.* 11 (2024) 674–691, <https://doi.org/10.1016/j.egyrs.2023.07.028>.
- [63] L. Mayrhofer, A. Müller, M. Bügelmayr-Blaschek, A. Malla, L. Kranzl, Modelling the effect of passive cooling measures on future energy needs for the Austrian building stock, *Energ. Buildings* 296 (2023), <https://doi.org/10.1016/j.enbuild.2023.113333>.
- [64] R. Büchele, L. Kranzl, M. Hartner, J. Hasani, Opportunities and challenges of future district heating portfolios of an austrian utility, *Energies* 13 (10) (2020), <https://doi.org/10.3390/en13102457>.
- [65] C. Monsberger, K. Maggauer, B. Fina, D. Suna, C. Fuchs, B. Leitner, Profitability of biomass-based district heating considering different technology combinations and building flexibility, *Renewable and Sustainable Energy Transition* 4 (2023), <https://doi.org/10.1016/j.rset.2023.100062>.
- [66] S. Zwickl-Bernhard, M. Otti, Is the decarbonization of the European energy system driving district heating in Norway?, in: International Conference on the European Energy Market, EEM IEEE Computer Society, 2023 <https://doi.org/10.1109/EEM58374.2023.10161986>.
- [67] J. Ramsebner, P. Linares, R. Haas, Estimating storage needs for renewables in Europe: the correlation between renewable energy sources and heating and cooling demand, *Smart Energy* 3 (2021), <https://doi.org/10.1016/j.segy.2021.100038>.
- [68] G. Dermentzis, F. Ochs, A. Thuer, W. Streicher, Supporting decision-making for heating and distribution systems in a new residential district - an Austrian case study, *Energy* 224 (2021), <https://doi.org/10.1016/j.energy.2021.120141>.
- [69] F. Ochs, A. Dahash, A. Tosatto, M. Bianchi Janetti, Techno-economic planning and construction of cost-effective large-scale hot water thermal energy storage for Renewable District heating systems, *Renew. Energy* 150 (2020) 1165–1177, <https://doi.org/10.1016/j.renene.2019.11.017>.
- [70] F. Ochs, M. Magni, G. Dermentzis, Integration of heat pumps in buildings and district heating systems—evaluation on a building and energy system level, *Energies* 15 (11) (2022), <https://doi.org/10.3390/en15113889>.
- [71] F. Ochs, M. Magni, M. Hauer, S. De Vries, P. Bonato, Simulation based evaluation of building integrated solar envelope systems on building level, in: L.J.B.W.H. L. Saelens D (Ed.), Building Simulation Conference Proceedings, International Building Performance Simulation Association, 2022, pp. 94–101, <https://doi.org/10.26868/25222708.2021.30222>.
- [72] A. Tosatto, A. Dahash, F. Ochs, Simulation-based performance evaluation of large-scale thermal energy storage coupled with heat pump in district heating systems, *J. Energy Storage* 61 (2023), <https://doi.org/10.1016/j.est.2023.106721>.
- [73] A. Tosatto, F. Ochs, Performance comparison of large-scale thermal energy storage and hydrogen as seasonal storage for achieving energy autarky in residential districts with different renovation levels, *J. Energy Storage* 98 (2024), <https://doi.org/10.1016/j.est.2024.113009>.
- [74] A. Tosatto, F. Ochs, W. Streicher, M. Magni, E. Venturi, Methodology for the calculation of energy scenarios to achieve carbon neutrality in the building stock, in: Building Simulation Conference Proceedings, International Building Performance Simulation Association, 2023, pp. 2394–2401, <https://doi.org/10.26868/25222708.2023.1489>.
- [75] R. Gaugl, M. Sommer, C. Kettner, U. Bachhiesl, T. Klatzer, L. Gruber, M. Böheim, K. Kratena, S. Wogrin, Integrated power and economic analysis of Austria's renewable electricity transformation, *Energies* 16 (5) (2023), <https://doi.org/10.3390/en16052229>.
- [76] T. Klatzer, U. Bachhiesl, S. Wogrin, State-of-the-art expansion planning of integrated power, natural gas, and hydrogen systems, *Int. J. Hydrogen Energy* 47 (47) (2022) 20585–20603, <https://doi.org/10.1016/j.ijhydene.2022.04.293>.
- [77] T. Klatzer, U. Bachhiesl, S. Wogrin, A. Tomasgard, Assessing the impact of natural gas and hydrogen blending in integrated energy system modeling, in: IEEE Power and Energy Society General Meeting, IEEE Computer Society, 2023, <https://doi.org/10.1109/PESGM52003.2023.10252405>.
- [78] T. Klatzer, U. Bachhiesl, S. Wogrin, A. Tomasgard, Ramping up the hydrogen sector: an energy system modeling framework, *Appl. Energy* 355 (2024), <https://doi.org/10.1016/j.apenergy.2023.122264>.
- [79] S. Wogrin, D.A. Tejada-Arango, R. Gaugl, T. Klatzer, U. Bachhiesl, LEGO: the open-source low-carbon expansion generation optimization model, *SoftwareX* 19 (2022), <https://doi.org/10.1016/j.softx.2022.101141>.
- [80] R. Gaugl, U. Bachhiesl, Potentials and systemic aspects for the integration of renewable energies in the North African and Middle Eastern electricity system, *Elektrotechnik und Informationstechnik* 137 (8) (2020) 487–494, <https://doi.org/10.1007/s00502-020-00848-z>.
- [81] S. Wogrin, Time series aggregation for optimization: one-size-fits-all? *IEEE Transactions on Smart Grid* 14 (3) (2023) 2489–2492, <https://doi.org/10.1109/TSG.2023.3242467>.
- [82] D. Cardona-Vasquez, T. Klatzer, B. Klinz, S. Wogrin, Enhancing time series aggregation for power system optimization models: incorporating network and ramping constraints, *Electr. Power Syst. Res.* 230 (2024), <https://doi.org/10.1016/j.eprsr.2024.110267>.
- [83] R. Haas, C. Kemfert, H. Auer, A. Ajanovic, M. Sayer, A. Hiesl, On the economics of storage for electricity: current state and future market design prospects, *Wiley Interdisciplinary Reviews: Energy and Environment* 11 (3) (2022), <https://doi.org/10.1002/wene.431>.
- [84] C. Loschan, H. Auer, G. Lettner, Synergies and competition: examining flexibility options in the European electricity market, *Int. J. Electr. Power Energy Syst.* 159 (2024), <https://doi.org/10.1016/j.ijepes.2024.109992>.
- [85] M. Mallet, C. Loschan, D. Schwabeneder, G. Lettner, H. Auer, Business models for local energy market and circular economy establishment in municipalities: a case study in an Austrian municipality, *Heliyon* 9 (10) (2023), <https://doi.org/10.1016/j.heliyon.2023.e20776>.
- [86] M. Mallet, D. Schwabeneder, G. Lettner, C. Loschan, C. Corinaldesi, H. Auer, Local sustainable communities: sector coupling and community optimization in decentralized energy systems, *Cleaner Energy Syst.* 7 (2024), <https://doi.org/10.1016/j.cles.2023.100106>.
- [87] S. Zwickl-Bernhard, H. Auer, Citizen participation in low-carbon energy systems: energy communities and its impact on the electricity demand on neighborhood and national level, *Energies* 14 (2) (2021), <https://doi.org/10.3390/en14020305>.
- [88] S. Zwickl-Bernhard, H. Auer, Demystifying natural gas distribution grid decommissioning: an open-source approach to local deep decarbonization of urban neighborhoods, *Energy* 238 (2022), <https://doi.org/10.1016/j.energy.2021.121805>.
- [89] C. Corinaldesi, G. Lettner, H. Auer, On the characterization and evaluation of residential on-site E-car-sharing, *Energy* 246 (2022), <https://doi.org/10.1016/j.energy.2022.123400>.
- [90] C. Loschan, D. Schwabeneder, G. Lettner, H. Auer, Flexibility potential of aggregated electric vehicle fleets to reduce transmission congestions and redispatch needs: a case study in Austria, *Int. J. Electr. Power Energy Syst.* 146 (2023), <https://doi.org/10.1016/j.ijepes.2022.108802>.
- [91] A. Golab, S. Zwickl-Bernhard, H. Auer, Minimum-cost fast-charging infrastructure planning for electric vehicles along the Austrian high-level road network, *Energies* 15 (6) (2022), <https://doi.org/10.3390/en15062147>.
- [92] M. Mansoor, M. Stadler, H. Auer, M. Zellinger, Advanced optimal planning for microgrid technologies including hydrogen and mobility at a real microgrid testbed, *Int. J. Hydrogen Energy* 46 (37) (2021) 19285–19302, <https://doi.org/10.1016/j.ijhydene.2021.03.110>.
- [93] T. Perger, H. Auer, Energy efficient route planning for electric vehicles with special consideration of the topography and battery lifetime, *Energ. Effic.* 13 (8) (2020) 1705–1726, <https://doi.org/10.1007/s12053-020-09900-5>.
- [94] A. Hiesl, J. Ramsebner, R. Haas, Modelling stochastic electricity demand of electric vehicles based on traffic surveys—the case of Austria, *Energies* 14 (6) (2021), <https://doi.org/10.3390/en14061577>.
- [95] G.M. Castro, C. Klöckl, P. Regner, J. Schmidt, A.O. Pereira Jr., Improvements to Modern Portfolio Theory based models applied to electricity systems, *Energy Econ.* 111 (2022), <https://doi.org/10.1016/j.eneco.2022.106047>.
- [96] C. Mikovits, E. Wetterlund, S. Wehrle, J. Baumgartner, J. Schmidt, Stronger together: multi-annual variability of hydrogen production supported by wind power in Sweden, *Appl. Energy* 282 (2021), <https://doi.org/10.1016/j.apenergy.2020.116082>.
- [97] S. Wehrle, K. Gruber, J. Schmidt, The cost of undisturbed landscapes, *Energy Policy* 159 (2021), <https://doi.org/10.1016/j.enpol.2021.112617>.
- [98] N. Vulic, S. Eggimann, M. Sulzer, K. Orehoung, National building stock model for evaluating the impact of different retrofit measures, in: S.B.S.Y.W.C.L.D.L.D.L. D. Andersen M (Ed.), Journal of Physics: Conference Series, Institute of Physics, 2023, <https://doi.org/10.1088/1742-6596/2600/3/032004>.
- [99] E. Thrampoulidis, K. Orehoung, G. Hug, Electricity demand flexibility potential of optimal building retrofit solutions, in: S.B.L.D. Scartezini J.L (Ed.), Journal of Physics: Conference Series, IOP Publishing Ltd, 2021, <https://doi.org/10.1088/1742-6596/2042/1/012149>.
- [100] J. Rousseau, H. Cai, P. Heer, K. Orehoung, G. Hug, Uncertainty-aware energy flexibility quantification of a residential building, in: IEEE PES Innovative Smart Grid Technologies Conference Europe, IEEE Computer Society, 2023, <https://doi.org/10.1109/ISGTUEUROPE56780.2023.10407489>.
- [101] J. Go, J. Byun, K. Orehoung, Y. Heo, Battery-H2 storage system for self-sufficiency in residential buildings under different electric heating system scenarios, *Appl. Energy* 337 (2023), <https://doi.org/10.1016/j.apenergy.2023.120742>.
- [102] E. Thrampoulidis, G. Mavromatidis, A. Lucchi, K. Orehoung, A machine learning-based surrogate model to approximate optimal building retrofit solutions, *Appl. Energy* 281 (2021), <https://doi.org/10.1016/j.apenergy.2020.116024>.
- [103] A.D. Valle, S. Wogrin, J. Reneses, Multi-objective bi-level optimization model for the investment in gas infrastructures, *Energ. Strat. Rev.* 30 (2020), <https://doi.org/10.1016/j.esr.2020.100492>.
- [104] M.A. Gonzalez-Sierra, S. Wogrin, The importance of modeling operational constraints in combined-cycle units to support energy transition, in: N. A. Mendoza PS (Ed.), 1st IEEE Colombian Caribbean Conference, C3 2023,

- Institute of Electrical and Electronics Engineers Inc., 2023, <https://doi.org/10.1109/C358072.2023.10436182>.
- [105] S. Cejka, D. Reihns, B. Fina, M. Stefan, D. Hauer, F. Zeilinger, Typical future energy communities - an analysis on operational areas, member structure and used infrastructure, IET Conference Proceedings 2022 (3) (2022) 498–502, <https://doi.org/10.1049/icp.2022.0757>.
- [106] B. Fina, H. Auer, Economic viability of renewable energy communities under the framework of the renewable energy directive transposed to Austrian law, *Energies* 13 (21) (2020), <https://doi.org/10.3390/en13215743>.
- [107] B. Fina, C. Monsberger, Measures and business model approaches to facilitate the diffusion and integration of energy communities—a special focus on the Austrian case, *Energ. Strat. Rev.* 49 (2023), <https://doi.org/10.1016/j.esr.2023.101161>.
- [108] B. Fina, C. Monsberger, H. Auer, A framework to estimate the large-scale impacts of energy community roll-out, *Heliyon* 8 (7) (2022), <https://doi.org/10.1016/j.heliyon.2022.e09905>.
- [109] B. Fina, C. Monsberger, H. Auer, Simulation or estimation?—two approaches to calculate financial benefits of energy communities, *J. Clean. Prod.* 330 (2022), <https://doi.org/10.1016/j.jclepro.2021.129733>.
- [110] I. Mariuzzo, B. Fina, S. Stroemer, M. Raugi, Economic assessment of multiple energy community participation, *Appl. Energy* 353 (2024), <https://doi.org/10.1016/j.apenergy.2023.122060>.
- [111] C. Monsberger, B. Fina, H. Auer, Profitability of energy supply contracting and energy sharing concepts in a neighborhood energy community: business cases for Austria, *Energies* 14 (4) (2021), <https://doi.org/10.3390/en14040921>.
- [112] C. Monsberger, T. Forster, Impact of CO₂ pricing on cost savings in energy communities, in: International Conference on the European Energy Market, EEM, IEEE Computer Society, 2023, <https://doi.org/10.1109/EEM58374.2023.10161858>.
- [113] B. Fina, M. Schwebler, C. Monsberger, Different technologies' impacts on the economic viability, energy flows and emissions of energy communities, *Sustainability* 14 (9) (2022), <https://doi.org/10.3390/su14094993>.
- [114] R. Geyer, J. Krail, B. Leitner, R.R. Schmidt, P. Leoni, Energy-economic assessment of reduced district heating system temperatures, *Smart Energy* 2 (2021), <https://doi.org/10.1016/j.segy.2021.100011>.
- [115] N. Marx, R. Blakcori, T. Forster, K. Maggauer, R. Schmidt, Risk assessment in district heating: evaluating the economic risks of inter-regional heat transfer networks with regards to uncertainties of energy prices and waste heat availability using Monte Carlo simulations, *Smart Energy* 12 (2023), <https://doi.org/10.1016/j.segy.2023.100119>.
- [116] C. Loschan, D. Schwabeneder, M. Maltet, G. Lettner, H. Auer, Hydrogen as short-term flexibility and seasonal storage in a sector-coupled electricity market, *Energies* 16 (14) (2023), <https://doi.org/10.3390/en16145333>.
- [117] J. Radl, A. Fleischhacker, F.H. Revheim, G. Lettner, H. Auer, Comparison of profitability of PV electricity sharing in renewable energy communities in selected European countries, *Energies* 13 (18) (2020), <https://doi.org/10.3390/en13195007>.
- [118] T. Perger, H. Auer, Dynamic participation in local energy communities with peer-to-peer trading, *Open Research Europe* 2 (2022), <https://doi.org/10.12688/openresearch.14332.1>.
- [119] T. Perger, S. Zwickl-Bernhard, A. Golab, H. Auer, A stochastic approach to dynamic participation in energy communities Ein stochastischer Ansatz zur dynamischen Teilnahme an Energiegemeinschaften, *Elektrotech. Infotech.* 139 (8) (2022) 644–661, <https://doi.org/10.1007/s00502-022-01069-2>.
- [120] D. Putz, M. Gumhalter, H. Auer, The true value of a forecast: assessing the impact of accuracy on local energy communities, *Sustainable Energy, Grids and Networks* 33 (2023), <https://doi.org/10.1016/j.segan.2022.100983>.
- [121] N. Houben, A. Cosic, M. Stadler, M. Mansoor, M. Zellinger, H. Auer, A. Ajanovic, R. Haas, Optimal dispatch of a multi-energy system microgrid under uncertainty: a renewable energy community in Austria, *Appl. Energy* 337 (2023), <https://doi.org/10.1016/j.apenergy.2023.120913>.
- [122] N. Efkarpidis, S. Imoscoli, A. Bratukhin, R. Brannvall, G. Franzl, T. Leopold, V. Bauer, A. Goranovic, S. Wilker, C.W. Yang, J. Gustafsson, M. Geidl, T. Sauter, Proactive scheduling of mixed energy resources at different grid levels, *IEEE Transactions on Sustainable Energy* 15 (2) (2024) 952–963, <https://doi.org/10.1109/TSTE.2023.3320055>.
- [123] G. Franzl, T. Leopold, S. Wilker, T. Sauter, Flexibility offering and rating for multi-objective energy balancing, in: IEEE International Conference on Emerging Technologies and Factory Automation, ETFA, Institute of Electrical and Electronics Engineers Inc., 2021, <https://doi.org/10.1109/ETFA45728.2021.9613188>.
- [124] G. Franzl, S. Wilker, N. Efkarpidis, T. Sauter, Situation awareness by simple intuitive traffic light signals for smart utilisation of local demand and supply flexibility, *Energies* 15 (3) (2022), <https://doi.org/10.3390/en15031001>.
- [125] S. Howind, V. Bauer, A. Wendt, G. Franzl, T. Sauter, S. Wilker, Prosumer and demand-side management impact on rural communities' energy balance, in: IEEE International Conference on Emerging Technologies and Factory Automation, ETFA, Institute of Electrical and Electronics Engineers Inc., 2020, pp. 768–773, <https://doi.org/10.1109/ETFA46521.2020.9212185>.
- [126] T. Leopold, V. Bauer, A. Brathukin, D. Hauer, S. Wilker, G. Franzl, R. Mosshammer, T. Sauter, Simulation-based methodology for optimizing energy community controllers, in: IEEE International Symposium on Industrial Electronics, Institute of Electrical and Electronics Engineers Inc., 2021, <https://doi.org/10.1109/ISIE45552.2021.9576277>.
- [127] G. Franzl, S. Wilker, T. Sauter, Multi-Level Traffic Light Signals Integrating Energy Market and Grid Needs, in: IEEE PES Innovative Smart Grid Technologies Conference Europe, IEEE Computer Society, 2023, <https://doi.org/10.1109/ISGTEUROPE56780.2023.10408341>.
- [128] S.G. Amores, E. Hillberg, A. Iliceto, E. Matacz, A. Ilo, How can flexibility support power grid resilience through the next level of flexibility and alternative grid developments, IET Conference Proceedings (2023) 1842–1846, <https://doi.org/10.1049/icp.2023.1039>.
- [129] H. Bruckner, M. Adamcová, A. Ilo, A. Werner, Interact - integration of innovative technologies of peds into a holistic architecture, in: H.P.T.J.H.J.L.A. Sojkova K (Ed.), Acta Polytechnica CTU Proceedings, Czech Technical University in Prague, 2022, pp. 288–294, <https://doi.org/10.14311/APP.2022.38.0288>.
- [130] H. Bruckner, M. Olofsgard, A. Ilo, M. Adamcova, Viable link-based energy community: increasing flexibility and resilience of electricity infrastructure, IET Conference Proceedings (2023) 332–336, <https://doi.org/10.1049/icp.2023.0303>.
- [131] A. Ilo, Use cases in sector coupling as part of the LINK-based holistic architecture to increase the grid flexibility, in: CIRED - Open Access Proceedings Journal, Institution of Engineering and Technology, 2020, pp. 529–532, <https://doi.org/10.1049/oap-cired.2021.0108>.
- [132] A. Ilo, H. Bruckner, M. Olofsgard, M. Adamcova, Deploying e-mobility in the interact energy community to promote additional and valuable flexibility resources for secure and efficient grid operation, IET Conference Proceedings 2022 (3) (2022) 162–166, <https://doi.org/10.1049/icp.2022.0685>.
- [133] A. Ilo, H. Bruckner, M. Olofsgard, M. Adamcova, A. Werner, Viable fully integrated energy community based on the holistic LINK approach, *Energies* 16 (6) (2023), <https://doi.org/10.3390/en16062935>.
- [134] A. Ilo, D.L. Schultis, Holistic architecture*, in: Power Systems, 2022, pp. 27–132, https://doi.org/10.1007/978-3-030-81530-1_2.
- [135] N. Efthymiopoulos, P. Makris, G. Tsasouglou, K. Steriotis, D.J. Vergados, A. Khaksari, L. Herre, V. Lacort, G. Martinez, E.L. Lorente, R. Gehrcke, M. Bagherpour, F. Milzer, B. Pellerin, F. Farrukh, M. Thoma, T. Tadin, M.I. Baka, C. Papadimitriou, A. Kyprianou, G.E. Georghiou, H. Pandzic, D. Badanjak, S. Chatzivasileiadis, E. Prat, M. Calin, T. Esterl, F. Prösl, Andrén, E. Varvarigos, Flexgrid – a novel smart grid architecture that facilitates high-RES penetration through innovative flexibility markets towards efficient stakeholder interaction, *Open Research Europe* 1 (2023), <https://doi.org/10.12688/openresearch.14109.2>.
- [136] H.M. Neumann, A. Hainoun, R. Stollnberger, G. Etminan, V. Schaffler, Analysis and evaluation of the feasibility of positive energy districts in selected urban typologies in Vienna using a bottom-up district energy modelling approach, *Energies* 14 (15) (2021), <https://doi.org/10.3390/en14154449>.
- [137] H. Böhm, M. Lehner, T. Kienberger, Techno-economic assessment of thermally integrated co-electrolysis and methanation for industrial closed carbon cycles, *Frontiers in Sustainability* 2 (2021), <https://doi.org/10.3389/frsus.2021.726332>.
- [138] P. Nagovnak, M. Rahnama Mobarakeh, C. Diendorfer, G. Thenius, H. Böhm, T. Kienberger, Cost-driven assessment of technologies' potential to reach climate neutrality in energy-intensive industries, *Energies* 17 (5) (2024), <https://doi.org/10.3390/en17051058>.
- [139] S. Puschnigg, S. Knöttner, J. Lindorfer, T. Kienberger, Development of the virtual battery concept in the paper industry: applying a dynamic life cycle assessment approach, *Sustainable Prod. Consumption* 40 (2023) 438–457, <https://doi.org/10.1016/j.spc.2023.07.013>.
- [140] S. Hochmeister, L. Kühberger, J. Kulich, H. Ott, T. Kienberger, A methodology for the determination of future carbon management strategies: a case study of Austria, *International Journal of Sustainable Energy Planning and Management* 41 (2024) 108–124, <https://doi.org/10.54337/ijsep.8280>.
- [141] S. Hochmeister, L. Kühberger, J. Kulich, H. Ott, T. Kienberger, Carbon management for a climate-neutral Austria Carbon Management für ein klimaneutrales Österreich, *Elektrotech. Informationtech.* (2024), <https://doi.org/10.1007/s00502-024-01235-8>.
- [142] T. Kienberger, NEFI - new energy for industry NEFI – new energy for industry, *Elektrotech. Infotech.* 138 (4–5) (2021) 257, <https://doi.org/10.1007/s00502-021-00898-x>.
- [143] P. Nagovnak, C. Schützenhofer, M. Rahnama Mobarakeh, R. Cvetkovska, S. Stortecy, A. Hainoun, V. Alton, T. Kienberger, Assessment of technology-based options for climate neutrality in Austrian manufacturing industry, *Heliyon* 10 (3) (2024), <https://doi.org/10.1016/j.heliyon.2024.e25382>.
- [144] M. Rahnama Mobarakeh, T. Kienberger, Climate neutrality strategies for energy-intensive industries: an Austrian case study, *Cleaner Engineering and Technology* 10 (2022), <https://doi.org/10.1016/j.clet.2022.100545>.
- [145] R. Geyer, S. Knöttner, C. Diendorfer, G. Drexler-schmid, V. Alton, 100% renewable energy for Austria's industry: scenarios, energy carriers and infrastructure requirements, *Appl. Sci. (Switz.)* 11 (4) (2021) 1–18, <https://doi.org/10.3390/app11041819>.
- [146] R. Geyer, C. Diendorfer, S. Knöttner, G. Drexler-Schmid, 100% renewable energy for Austria's industry: alternative energy sources and infrastructure requirements, in: Eceee Industrial Summer Study Proceedings, European Council for an Energy Efficient Economy, 2020, pp. 395–404.
- [147] C. Sejkora, J. Lindorfer, L. Kühberger, T. Kienberger, Interlinking the renewable electricity and gas sectors: a techno-economic case study for Austria, *Energies* 14 (19) (2021), <https://doi.org/10.3390/en14196289>.
- [148] D.C. Rosenfeld, J. Lindorfer, H. Böhm, A. Zauner, K. Fazeni-Fraisil, Potentials and costs of various renewable gases: a case study for the Austrian energy system by 2050, *Detritus* 16 (2021) 106–120, <https://doi.org/10.31025/2611-4135/2021.15121>.

- [149] V. Rodin, J. Lindorfer, H. Böhm, L. Vieira, Assessing the potential of carbon dioxide valorisation in Europe with focus on biogenic CO₂, *J. CO₂ Util.* 41 (2020), <https://doi.org/10.1016/j.jcou.2020.101219>.
- [150] G. Bachner, J. Mayer, K.W. Steininger, A. Anger-Kraavi, A. Smith, T.S. Barker, Uncertainties in macroeconomic assessments of low-carbon transition pathways - the case of the European iron and steel industry, *Ecol. Econ.* 172 (2020), <https://doi.org/10.1016/j.ecolecon.2020.106631>.
- [151] M.C. Unegg, K.W. Steininger, C. Ramsauer, M. Rivera-Aguilar, Assessing the environmental impact of waste management: a comparative study of CO₂ emissions with a focus on recycling and incineration, *J. Clean. Prod.* 415 (2023), <https://doi.org/10.1016/j.jclepro.2023.137745>.
- [152] G. Bachner, B. Wolkinger, J. Mayer, A. Türk, K.W. Steininger, Risk assessment of the low-carbon transition of Austria's steel and electricity sectors, *Environ. Innov. Soc. Trans.* 35 (2020) 309–332, <https://doi.org/10.1016/j.eist.2018.12.005>.
- [153] T. Fahn, G. Bachner, R. Beach, J. Chateau, S. Fujimori, M. Ghosh, M. Hamdi-Cherif, E. Lanzi, S. Paltsev, T. Vandyck, B. Cunha, R. Garaffa, K. Steininger, Capturing key energy and emission trends in cge models: assessment of status and remaining challenges, *Journal of Global Economic Analysis* 5 (1) (2020) 196–272, <https://doi.org/10.21642/JGEA.050106AF>.
- [154] J.A. Duro, A. Perez-Laborda, M. Löw, S. Matej, B. Plank, F. Krausmann, D. Wiedenhofer, H. Haberl, Spatial patterns of built structures co-determine nations' level of resource demand, *Journal of Industrial Ecology* 28 (2) (2024) 289–302, <https://doi.org/10.1111/jiec.13470>.
- [155] O. Galychyn, B.D. Fath, D. Wiedenhofer, E. Buonocore, P.P. Franzese, An urban energy footprint: comparing supply- and use-extended input-output models for the case of Vienna, Austria, *Cleaner Production Letters* 6 (2024), <https://doi.org/10.1016/j.clpl.2024.100058>.
- [156] A. Gómez-Sanabria, G. Kiesewetter, Z. Klimont, W. Schoepp, H. Haberl, Potential for future reductions of global GHG and air pollutants from circular waste management systems, *Nat. Commun.* 13 (1) (2022), <https://doi.org/10.1038/s41467-021-27624-7>.
- [157] F. Krausmann, C. Lauk, W. Haas, D. Wiedenhofer, From resource extraction to outflows of wastes and emissions: the socioeconomic metabolism of the global economy, 1900–2015, *Glob. Environ. Chang.* 52 (2018) 131–140, <https://doi.org/10.1016/j.gloenvcha.2018.07.003>.
- [158] B. Smetschka, D. Wiedenhofer, C. Egger, E. Haselsteiner, D. Moran, V. Gaube, Time matters: the carbon footprint of everyday activities in Austria, *Ecol. Econ.* 164 (2019), <https://doi.org/10.1016/j.ecolecon.2019.106357>.
- [159] J. Streeck, H. Wieland, S. Pauliuk, B. Plank, K. Nakajima, D. Wiedenhofer, A review of methods to trace material flows into final products in dynamic material flow analysis: comparative application of six methods to the United States and EXIOBASE3 regions, part 2, *Journal of Industrial Ecology* 27 (2) (2023) 457–475, <https://doi.org/10.1111/jiec.13379>.
- [160] D. Wiedenhofer, A. Baumgart, S. Matej, D. Virág, G. Kalt, M. Lanau, D.D. Tingley, Z. Liu, J. Guo, H. Tanikawa, H. Haberl, Mapping and modelling global mobility infrastructure stocks, material flows and their embodied greenhouse gas emissions, *J. Clean. Prod.* 434 (2024), <https://doi.org/10.1016/j.jclepro.2023.139742>.
- [161] D. Virág, D. Wiedenhofer, A. Baumgart, S. Matej, F. Krausmann, J. Min, N.D. Rao, H. Haberl, How much infrastructure is required to support decent mobility for all? An exploratory assessment, *Ecol. Econ.* 200 (2022), <https://doi.org/10.1016/j.ecolecon.2022.107511>.
- [162] D. Virág, D. Wiedenhofer, W. Haas, H. Haberl, G. Kalt, F. Krausmann, The stock-flow-service nexus of personal mobility in an urban context: Vienna, Austria, *Environ. Dev.* 41 (2022), <https://doi.org/10.1016/j.envdev.2021.100628>.
- [163] G. Kalt, P. Thunshirn, H. Haberl, A global inventory of electricity infrastructures from 1980 to 2017: country-level data on power plants, grids and transformers, *Data Brief* 38 (2021), <https://doi.org/10.1016/j.dib.2021.107351>.
- [164] G. Kalt, P. Thunshirn, F. Krausmann, H. Haberl, Material requirements of global electricity sector pathways to 2050 and associated greenhouse gas emissions, *J. Clean. Prod.* 358 (2022), <https://doi.org/10.1016/j.jclepro.2022.132014>.
- [165] A. Amann, N. Weber, J. Krampe, H. Rechberger, S. Peer, M. Zessner, O. Zoboli, Systematic data-driven exploration of Austrian wastewater and sludge treatment - implications for phosphorus governance, costs and environment, *Sci. Total Environ.* 846 (2022), <https://doi.org/10.1016/j.scitotenv.2022.157401>.
- [166] A. Amann, N. Weber, J. Krampe, H. Rechberger, O. Zoboli, M. Zessner, Operation and performance of Austrian wastewater and sewage sludge treatment as a basis for resource optimization, *Water (Switzerland)* 13 (21) (2021), <https://doi.org/10.3390/w13212998>.
- [167] A. Long, N. Weber, J. Krampe, S. Peer, H. Rechberger, M. Zessner, O. Zoboli, Multi-criteria analysis of strategies towards sustainable recycling of phosphorus from sewage sludge in Austria, *J. Environ. Manage.* 362 (2024), <https://doi.org/10.1016/j.jenvman.2024.121339>.
- [168] A. Parchomenko, D. Nelen, J. Gillabel, K.C. Vrancken, H. Rechberger, Resource effectiveness of the European automotive sector – a statistical entropy analysis over time, *Resour. Conserv. Recycl.* 169 (2021), <https://doi.org/10.1016/j.resconrec.2021.105558>.
- [169] C. Roithner, O. Cencic, M. Honic, H. Rechberger, Recyclability assessment at the building design stage based on statistical entropy: a case study on timber and concrete building, *Resources, Conservation and Recycling* 184 (2022), <https://doi.org/10.1016/j.resconrec.2022.106407>.
- [170] S.A. Rothwell, D.G. Doody, C. Johnston, K.J. Forber, O. Cencic, H. Rechberger, P. J.A. Withers, Phosphorus stocks and flows in an intensive livestock dominated food system, *Resour. Conserv. Recycl.* 163 (2020), <https://doi.org/10.1016/j.resconrec.2020.105065>.
- [171] S. Schützenhofer, I. Kovacic, H. Rechberger, Assessment of sustainable use of material resources in the architecture, engineering and construction industry – a conceptual framework proposal for Austria, *Journal of Sustainable Development of Energy, Water and Environment Systems* 10 (4) (2022), <https://doi.org/10.13044/j.sdewes.d10.0417>.
- [172] S. Schützenhofer, I. Kovacic, H. Rechberger, S. Mack, Improvement of environmental sustainability and circular economy through construction waste management for material reuse, *Sustainability (Switzerland)* 14 (17) (2022), <https://doi.org/10.3390/su141711087>.
- [173] J. Tanzer, H. Rechberger, Complex system, simple indicators: evaluation of circularity and statistical entropy as indicators of sustainability in Austrian nutrient management, *Resources, Conservation and Recycling* 162 (2020), <https://doi.org/10.1016/j.resconrec.2020.104961>.
- [174] K. Vulsteke, S. Huysveld, G. Thomassen, A. Beylot, H. Rechberger, J. Dewulf, What is the meaning of value in a circular economy? A conceptual framework, *Resour. Conserv. Recycl.* 207 (2024), <https://doi.org/10.1016/j.resconrec.2024.107687>.
- [175] A. Winterstetter, S. Heuss-Assbichler, J. Stegemann, U. Kral, P. Wäger, M. Osmani, H. Rechberger, The role of anthropogenic resource classification in supporting the transition to a circular economy, *J. Clean. Prod.* 297 (2021), <https://doi.org/10.1016/j.jclepro.2021.126753>.
- [176] I.K.M. Yu, H. Rechberger, J. Gutberlet, I.R. Istrate, K. Parizeau, M. Sanctuary, H. McQuillan, M. Dutra de Barcellos, Closing the waste gap, *One Earth* 5 (11) (2022) 1181–1184, <https://doi.org/10.1016/j.oneear.2022.10.015>.
- [177] Y. Zhou, J. Li, H. Rechberger, G. Wang, S. Chen, W. Xing, P. Li, Dynamic criticality of by-products used in thin-film photovoltaic technologies by 2050, *J. Clean. Prod.* 263 (2020), <https://doi.org/10.1016/j.jclepro.2020.121599>.
- [178] N. Alaux, T. Lackner, S. Nabernegg, B. Truger, M. Röck, K.W. Steininger, A. Passer, Carbon budget for national building stock life-cycle emissions: a novel approach, in: S.B.S.Y.W.C.L.D.L.D.L.D. Andersen M (Ed.), *Journal of Physics: Conference Series*, Institute of Physics, 2023, <https://doi.org/10.1088/1742-6596/2600/15/152004>.
- [179] N. Alaux, T.P. Obrecht, M.R.M. Saade, A. Passer, A need for sufficiency in the built environment: prospective life cycle assessment of the Austrian building stock, in: L.T.G.J.K.N.W.H. Foliente G (Ed.), *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2024, <https://doi.org/10.1088/1755-1315/1363/1/012002>.
- [180] N. Alaux, M. Ruschi Mendes Saade, A. Passer, Inventory regionalization of background data: influence on building life cycle assessment and carbon reduction strategies, *J. Clean. Prod.* 459 (2024), <https://doi.org/10.1016/j.jclepro.2024.142434>.
- [181] R. Di Bari, N. Alaux, M. Saade, S.H. Hong, R. Horn, A. Passer, Systematising the LCA approaches' soup: a framework based on text mining, *Int. J. Life Cycle Assess.* (2024), <https://doi.org/10.1007/s11367-024-02332-8>.
- [182] D. Maierhofer, N. Alaux, H. Vašátko, M. Saade, M. Stavric, A. Passer, The influence of biogenic carbon assessment assumptions on biogenic global warming results - case study of an innovative mycelium-based composite block, in: L.T.G.J.K.N.W.H. Foliente G (Ed.), *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2024, <https://doi.org/10.1088/1755-1315/1363/1/012060>.
- [183] D. Maierhofer, I. Zögl, M.R.M. Saade, A. Passer, The carbon dioxide storage potential of building materials: a systematic literature review, in: S.B.S.Y.W.C.L.D.L.D.L.D. Andersen M (Ed.), *Journal of Physics: Conference Series*, Institute of Physics, 2023, <https://doi.org/10.1088/1742-6596/2600/16/162003>.
- [184] C.M. Ouellet-Plamondon, M. Balouktsi, L. Delem, G. Foliente, N. Francart, A. Garcia-Martinez, E. Hoxha, T. Lützkendorf, F. Nygaard Rasmussen, B. Peuportier, J. Butler, H. Birgisdottir, L. Bragança, D. Dowdell, M. Dixit, V. Gomes, M. Gomes da Silva, J. Carlos Gómez, M. Kjendseth Wiik, M. Carmen Llatas Olivier, R. Mateus, L.M. Pulgrossi, M. Röck, M. Ruschi Mendes Saade, A. Passer, D. Satola, S. Seo, B. Soust-Verdaguer, J. Veselka, M. Volf, X. Zhang, R. Frischknecht, Comparison of 16 national methods in the life cycle assessment of carbon storage in wood products in a reference building, in: L.T.G.J.K.N.W.H. Foliente G (Ed.), *IOP Conference Series: Earth and Environmental Science*, Institute of Physics, 2024, <https://doi.org/10.1088/1755-1315/1363/1/012059>.
- [185] C.M. Ouellet-Plamondon, L. Ramseier, M. Balouktsi, L. Delem, G. Foliente, N. Francart, A. Garcia-Martinez, E. Hoxha, T. Lützkendorf, F. Nygaard Rasmussen, B. Peuportier, J. Butler, H. Birgisdottir, D. Dowdell, M.K. Dixit, V. Gomes, M. Gomes da Silva, J.C. Gómez de Cózar, M. Kjendseth Wiik, C. Llatas, R. Mateus, L.M. Pulgrossi, M. Röck, M.R.M. Saade, A. Passer, D. Satola, S. Seo, B. Soust-Verdaguer, J. Veselka, M. Volf, X. Zhang, R. Frischknecht, Carbon footprint assessment of a wood multi-residential building considering biogenic carbon, *J. Clean. Prod.* 404 (2023), <https://doi.org/10.1016/j.jclepro.2023.136834>.
- [186] M. Röck, A. Passer, K. Allacker, SLiCE: an open building data model for scalable high-definition life cycle engineering, dynamic impact assessment, and systematic hotspot analysis, *Sustainable Prod. Consumption* 45 (2024) 450–463, <https://doi.org/10.1016/j.spc.2024.01.005>.
- [187] K. Rasul, M. Bruckner, F. Mempel, S. Trsek, E.G. Hertwich, Energy input and food output: the energy imbalance across regional agri-food systems, *PNAS Nexus* 3 (12) (2024) pgae524, <https://doi.org/10.1093/pnasnexus/pgae524>.
- [188] H. Wieland, S. Giljum, N. Eisenmenger, D. Wiedenhofer, M. Bruckner, A. Schaffartzik, A. Owen, Supply versus use designs of environmental extensions in input-output analysis: conceptual and empirical implications for the case of energy, *Journal of Industrial Ecology* 24 (3) (2020) 548–563, <https://doi.org/10.1111/jiec.12975>.
- [189] M. Bruckner, R. Wood, D. Moran, N. Kuschig, H. Wieland, V. Maus, J. Börner, FABIO-the construction of the food and agriculture biomass input-output model,

- Environ. Sci. Technol. 53 (19) (2019) 11302–11312, <https://doi.org/10.1021/acs.est.9b03554>.
- [190] R. Asada, T. Krisztin, F. di Fulvio, F. Kraxner, T. Stern, Bioeconomic transition?: projecting consumption-based biomass and fossil material flows to 2050, *J. Ind. Ecol.* 24 (5) (2020) 1059–1073, <https://doi.org/10.1111/jiec.12988>.
- [191] A.L. Cowie, G. Berndes, N.S. Bentsen, M. Brandão, F. Cherubini, G. Egnell, B. George, L. Gustavsson, M. Hanewinkel, Z.M. Harris, F. Johnsson, M. Junginger, K.L. Kline, K. Koponen, J. Koppejan, F. Kraxner, P. Lamers, S. Majer, E. Marland, G.J. Nabuurs, L. Pelkmans, R. Sathre, M. Schaub, C.T. Smith Jr., S. Soimakallio, F. Van Der Hilst, J. Woods, F.A. Ximenes, Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy, *GCB Bioenergy* 13 (8) (2021) 1210–1231, <https://doi.org/10.1111/gcbb.12844>.
- [192] L. Eggemann, N. Escobar, R. Peters, P. Burauel, D. Stolten, Life cycle assessment of a small-scale methanol production system: a power-to-fuel strategy for biogas plants, *J. Clean. Prod.* 271 (2020), <https://doi.org/10.1016/j.jclepro.2020.122476>.
- [193] S.V. Hanssen, V. Daigloglou, Z.J.N. Steinmann, S. Frank, A. Popp, T. Brunelle, P. Lauri, T. Hasegawa, M.A.J. Huijbregts, D.P. Van Vuuren, Biomass residues as twenty-first century bioenergy feedstock—a comparison of eight integrated assessment models, *Clim. Change* 163 (3) (2020) 1569–1586, <https://doi.org/10.1007/s10584-019-02539-x>.
- [194] F. Harahap, S. Leduc, S. Mesfun, D. Khatiwada, F. Kraxner, S. Silveira, Meeting the bioenergy targets from palm oil based biorefineries: an optimal configuration in Indonesia, *Appl. Energy* 278 (2020), <https://doi.org/10.1016/j.apenergy.2020.115749>.
- [195] F. Harahap, A. Nurdiawati, D. Conti, S. Leduc, F. Urban, Renewable marine fuel production for decarbonised maritime shipping: pathways, policy measures and transition dynamics, *J. Clean. Prod.* 415 (2023), <https://doi.org/10.1016/j.jclepro.2023.137906>.
- [196] W. Li, P. Ciais, E. Stehfest, D. Van Vuuren, A. Popp, A. Arneft, F. Di Fulvio, J. Doelman, F. Humpeöder, A.B. Harper, T. Park, D. Makowski, P. Havlik, M. Obersteiner, J. Wang, A. Krause, W. Liu, Mapping the yields of lignocellulosic bioenergy crops from observations at the global scale, *Earth System Science Data* 12 (2) (2020) 789–804, <https://doi.org/10.5194/essd-12-789-2020>.
- [197] H. Mandova, P. Patrizio, S. Leduc, J. Kjærstad, C. Wang, E. Wetterlund, F. Kraxner, W. Gale, Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage, *J. Clean. Prod.* 218 (2019) 118–129, <https://doi.org/10.1016/j.jclepro.2019.01.247>.
- [198] M.N. Mohd Idris, H. Hashim, S. Leduc, P. Yowargana, F. Kraxner, K.S. Woon, Deploying bioenergy for decarbonizing Malaysian energy sectors and alleviating renewable energy poverty, *Energy* 232 (2021), <https://doi.org/10.1016/j.energy.2021.120967>.
- [199] N. Rinke Dias de Souza, G. Palma Petrielli, T.A. Dourado Hernandez, S. Leduc, F. Di Fulvio, D. de Souza Hensler, M. Ferreira Chagas, T. Lopes Junqueira, O. Cavalet, Bioenergy-livestock integration in Brazil: unraveling potentials for energy production and climate change mitigation, *J. Clean. Prod.* 422 (2023), <https://doi.org/10.1016/j.jclepro.2023.138586>.
- [200] S.K. Rose, A. Popp, S. Fujimori, P. Havlik, J. Weyant, M. Wise, D. van Vuuren, T. Brunelle, R.Y. Cui, V. Daigloglou, S. Frank, T. Hasegawa, F. Humpeöder, E. Kato, R.D. Sands, F. Sano, J. Tsutsui, J. Doelman, M. Muratori, R. Prudhomme, K. Wada, H. Yamamoto, Global biomass supply modeling for long-run management of the climate system, *Clim. Change* 172 (1–2) (2022), <https://doi.org/10.1007/s10584-022-03336-9>.
- [201] G. Seber, N. Escobar, H. Valin, R. Malina, Uncertainty in life cycle greenhouse gas emissions of sustainable aviation fuels from vegetable oils, *Renew. Sustain. Energy Rev.* 170 (2022), <https://doi.org/10.1016/j.rser.2022.112945>.
- [202] Y. Wu, A. Deppermann, P. Havlik, S. Frank, M. Ren, H. Zhao, L. Ma, C. Fang, Q. Chen, H. Dai, Global land-use and sustainability implications of enhanced bioenergy import of China, *Appl. Energy* 336 (2023), <https://doi.org/10.1016/j.apenergy.2023.120769>.
- [203] L. Mo, C.M. Zohner, P.B. Reich, J. Liang, S. de Miguel, G.J. Nabuurs, S.S. Renner, J. van den Hoogen, A. Araza, M. Herold, L. Mirzagholi, H. Ma, C. Averill, O. L. Phillips, J.G.P. Gamarra, I. Hordijk, D. Routh, M. Abegg, Y.C. Adou Yao, G. Alberti, A.M. Almeyda Zambrano, B.V. Alvarado, E. Alvarez-Dávila, P. Alvarez-Loayza, L.F. Alves, I. Amaral, C. Ammer, C. Antón-Fernández, A. Araujo-Murakami, L. Arroyo, V. Avitabile, G.A. Aymard, T.R. Baker, R. Balazy, O. Banki, J.G. Barroso, M.L. Bastian, J.F. Bastin, L. Birigazzi, P. Birnbaum, R. Bitariho, P. Boeckx, F. Bongers, O. Bouriaud, P.H.S. Brancalion, S. Brandl, F.Q. Brearley, R. Brienen, E.N. Broadbent, H. Bruielheide, F. Bussotti, R. Cazzolla Gatti, R. G. César, G. Cesljar, R.L. Chazdon, H.Y.H. Chen, C. Chisholm, H. Cho, E. Cienciala, C. Clark, D. Clark, G.D. Colletta, D.A. Coomes, F. Cornejo Valverde, J.J. Corral-Rivas, P.M. Crim, J.R. Cumming, S. Dayanandan, A.L. de Gasper, M. Decuyper, G. Derroire, B. DeVries, I. Djordjevic, J. Dolezal, A. Dourdain, N.L. Engone Obiang, B.J. Enquist, T.J. Eyre, A.B. Fandohan, T.M. Fayle, T. R. Feldpausch, L.V. Ferreira, L. Finér, M. Fischer, C. Fletcher, L. Frizzera, D. Gianelle, H.B. Glick, D.J. Harris, A. Hector, A. Hemp, G. Hengeveld, B. Hérault, J.L. Herbohn, A. Hillers, E.N. Honorio Coronado, C. Hui, T. Ibanez, N. Imai, A. M. Jagodziński, B. Jaroszewicz, V.K. Johannsen, C.A. Joly, T. Jucker, I. Jung, V. Karminov, K. Kartawinata, E. Kearsley, D. Kenfack, D.K. Kennard, S. Kepfer-Rojas, G. Keppel, M.L. Khan, T.J. Killeen, H.S. Kim, K. Kitayama, M. Köhl, H. Korjus, F. Kraxner, D. Kucher, D. Laarmann, M. Lang, H. Lu, N.V. Lukina, B. S. Maitner, Y. Malhi, E. Marcon, B.S. Marimon, B.H. Marimon-Junior, A. R. Marshall, E.H. Martin, J.A. Meave, O. Melo-Cruz, C. Mendoza, I. Mendoza-Polo, S. Misciaki, C. Merow, A. Montegudo Mendoza, V.S. Moreno, S.A. Mukul, P. Mundhenk, M.G. Nava-Miranda, D. Neill, V.J. Neldner, R.V. Nevenic, M. R. Ngugi, P.A. Niklaus, J. Oleksyn, P. Ontikov, E. Ortiz-Malavasi, Y. Pan, A. Paquette, A. Parada-Gutierrez, E.I. Parfenova, M. Park, M. Parren, N. Parthasarathy, P.L. Peri, S. Pfautsch, N. Picard, M.T.F. Piedade, D. Piotto, N.C. A. Pitman, A.D. Poulsen, J.R. Poulsen, H. Pretzsch, F. Ramirez Arevalo, Z. Restrepo-Correa, M. Rodeghiero, S.G. Rolim, A. Roopsind, F. Rovero, E. Rutishauser, P. Saikia, C. Salas-Eljatib, P. Saner, P. Schall, M.J. Schelhaas, D. Schepaschenko, M. Scherer-Lorenzen, B. Schmid, J. Schöngart, E.B. Searle, V. Seben, J.M. Serra-Diaz, D. Sheil, A.Z. Shvidenko, J.E. Silva-Espejo, M. Silveira, J. Singh, P. Sist, F. Slik, B. Sonké, A.F. Souza, K.J. Stereńczak, J.C. Svenning, M. Svoboda, B. Swanepoel, N. Targhetta, N. Tchekakova, H. ter Steege, R. Thomas, E. Tikhonova, P.M. Umunay, V.A. Usoltsev, R. Valencia, F. Valladares, F. van der Plas, T. Van Do, M.E. van Nuland, R.M. Vasquez, H. Verbeek, H. Viana, A.C. Vibrans, S. Vieira, K. von Gadow, H.F. Wang, J.V. Watson, G.D. A. Werner, S.K. Wiser, F. Wittmann, H. Woell, V. Wortel, R. Zagat, T. Zawila-Niedzwiecki, C. Zhang, X. Zhao, M. Zhou, Z.X. Zhu, I.C. Zo-Bi, G.D. Gann, T. W. Crowther, Integrated global assessment of the natural forest carbon potential, *Nature* 624 (7990) (2023) 92–101, <https://doi.org/10.1038/s41586-023-06723-z>.
- [204] I. Schulte, P. Yowargana, J.Ø. Nielsen, F. Kraxner, S. Fuss, Towards integration? Considering social aspects with large-scale computational models for nature-based solutions, *Global Sustainability* 7 (2024), <https://doi.org/10.1017/sus.2023.26>.
- [205] J.P.W. Scharlemann, R.C. Brock, N. Balfour, C. Brown, N.D. Burgess, M.K. Guth, D.J. Ingram, R. Lane, J.G.C. Martin, S. Wicander, V. Kapos, Towards understanding interactions between Sustainable Development Goals: the role of environment–human linkages, *Sustain. Sci.* 15 (6) (2020) 1573–1584, <https://doi.org/10.1007/s11625-020-00799-6>.
- [206] C.A. García-Velázquez, S. Leduc, Y. Van Der Meer, Use of optimization tools for decision-making: accounting for externalities in the production of biobased plastics, in: S.N.G.A.H.P. Mauguin P (Ed.), *European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies*, 2020, pp. 987–996.
- [207] J. Pedneault, G. Majeau-Bettez, V. Krey, M. Margni, What future for primary aluminium production in a decarbonizing economy? *Glob. Environ. Chang.* 69 (2021) <https://doi.org/10.1016/j.gloenvcha.2021.102316>.
- [208] M. Fuhrmann, C. Dißauer, C. Strasser, E. Schmid, An econometric analysis of the sawmill by-product market to explore bioeconomy options in Austria, *Biomass Bioenergy* 180 (2024), <https://doi.org/10.1016/j.biombioe.2023.107007>.
- [209] M. Fuhrmann, C. Dißauer, C. Strasser, E. Schmid, Scenario analysis of the Austrian sawmill by-product market using a supply and demand model, in: S.N.G.A. Chevet P-F (Ed.), *European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies*, 2022, pp. 309–313.
- [210] M. Fuhrmann, C. Dißauer, C. Strasser, E. Schmid, Analysing price cointegration of sawmill by-products in the forest-based sector in Austria, *Forest Policy Econ.* 131 (2021), <https://doi.org/10.1016/j.forpol.2021.102560>.
- [211] M. Fuhrmann, C. Dißauer, C. Strasser, E. Schmid, Price cointegration in the Austrian sawmill industry with a focus on by-products, in: S.N.G.A. Mauguin P (Ed.), *European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies*, 2021, pp. 1122–1126.
- [212] D. Bacovsky, C. Dißauer, M. Enigl, N. Ludwiczek, D. Matschegg, C. Pointner, A. Sonleitner, V. Kumar Verma, K. Kwant, L. Pelkmans, A. Wellinger, Bioenergy policies and status of implementation, in: *European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies*, 2017, pp. 2034–2040.
- [213] D. Bacovsky, J. Laurikko, The contribution of advanced renewable transport fuels to transport decarbonisation in 2030 and beyond, in: S.N.G.A.H.P. Mauguin P (Ed.), *European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies*, 2020, pp. 933–935.
- [214] D. Matschegg, A. Sonleitner, D. Bacovsky, Sustainable aviation fuels (Saf) production and challenges for market uptake, in: S.N.G.A. Bari ID (Ed.), *European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies*, 2023, pp. 1133–1136.
- [215] D. Matschegg, E. Carlon, R. Sturmlechner, A. Sonleitner, M. Fuhrmann, C. Dißauer, C. Strasser, M. Enigl, Investigation of individual motives and decision paths on residential energy supply systems, *Energy* 281 (2023), <https://doi.org/10.1016/j.energy.2023.128151>.
- [216] Y. Ermoliev, A.G. Zagorodny, V.L. Bogdanov, T. Ermolieva, P. Havlik, E. Rovenskaya, N. Komendantova, M. Obersteiner, Linking distributed optimization models for food, water, and energy security nexus management, *Sustainability (Switzerland)* 14 (3) (2022), <https://doi.org/10.3390/su14031255>.
- [217] Y. Ermoliev, A.G. Zagorodny, V.L. Bogdanov, T. Ermolieva, P. Havlik, E. Rovenskaya, N. Komendantova, M. Obersteiner, Robust food-energy–water–environmental security management: stochastic quasigradient procedure for linkage of distributed optimization models under asymmetric information and uncertainty, *Cybern. Syst. Anal.* 58 (1) (2022) 45–57, <https://doi.org/10.1007/s10559-022-00434-5>.
- [218] A. Palazzo, T. Kahil, B.A. Willaerts, P. Burek, M. van Dijk, T. Tang, P. Magnuszewski, P. Havlik, S. Langan, Y. Wada, Assessing sustainable development pathways for water, food, and energy security in a transboundary river basin, *Environ. Dev.* 51 (2024), <https://doi.org/10.1016/j.envdev.2024.101030>.
- [219] B. Zakeri, J.D. Hunt, M. Laldjebaev, V. Krey, A. Vinca, S. Parkinson, K. Riahi, Role of energy storage in energy and water security in Central Asia, *J. Energy Storage* 50 (2022), <https://doi.org/10.1016/j.est.2022.104587>.
- [220] M. Budzinski, R. Wood, B. Zakeri, V. Krey, A.H. Strömman, Coupling energy system models with multi-regional input-output models based on the make and use framework—insights from MESSAGEix and EXIOBASE, *Econ. Syst. Res.* (2023), <https://doi.org/10.1080/09535314.2022.2158065>.

- [221] O. Nishiura, V. Krey, O. Fricko, B. van Ruijven, S. Fujimori, Integration of energy system and computable general equilibrium models: an approach complementing energy and economic representations for mitigation analysis, *Energy* 296 (2024), <https://doi.org/10.1016/j.energy.2024.131039>.
- [222] M. Awais, A. Vinca, E. Byers, S. Frank, O. Fricko, E. Boere, P. Burek, M. Poblete Cazenave, P.N. Kishimoto, A. Mastrucci, Y. Satoh, A. Palazzo, M. McPherson, K. Riahi, V. Krey, MESSAGEix-GLOBIOM nexus module: integrating water sector and climate impacts, *Geosci. Model Dev.* 17 (6) (2024) 2447–2469, <https://doi.org/10.5194/gmd-17-2447-2024>.
- [223] M. Brinkerink, B. Zakeri, D. Huppmann, J. Glynn, B. Ó Gallachóir, P. Deane, Assessing global climate change mitigation scenarios from a power system perspective using a novel multi-model framework, *Environ. Modell. Softw.* 150 (2022), <https://doi.org/10.1016/j.envsoft.2022.105336>.
- [224] A. Vinca, K. Riahi, A. Rowe, N. Djilali, Climate-land-energy-water nexus models across scales: progress, gaps and best accessibility practices, *Front. Environ. Sci.* 9 (2021), <https://doi.org/10.3389/fenvs.2021.691523>.
- [225] N. Johnson, P. Burek, E. Byers, G. Falchetta, M. Flörke, S. Fujimori, P. Havlik, M. Hejazi, J. Hunt, V. Krey, S. Langan, N. Nakicenovic, A. Palazzo, A. Popp, K. Riahi, M. van Dijk, M.T.H. van Vliet, D.P. van Vuuren, Y. Wada, D. Wiberg, B. Willaarts, C. Zimm, S. Parkinson, Integrated solutions for the water-energy-land nexus: are global models rising to the challenge? *Water (Switzerland)* 11 (11) (2019), <https://doi.org/10.3390/w11112223>.
- [226] A. Vinca, S. Parkinson, E. Byers, P. Burek, Z. Khan, V. Krey, F.A. Diuana, Y. Wang, A. Ilyas, A.C. Köberle, I. Staffell, S. Pfenniger, A. Muhammad, A. Rowe, R. Schaeffer, N.D. Rao, Y. Wada, N. Djilali, K. Riahi, The Nexus Solutions Tool (NEST) v1.0: an open platform for optimizing multi-scale energy-water-land system transformations, *Geosci. Model Dev.* 13 (3) (2020) 1095–1121, <https://doi.org/10.5194/gmd-13-1095-2020>.
- [227] M. Schmidt, The Sankey diagram in energy and material flow management, *Journal of Industrial Ecology* 12 (1) (2008) 82–94, <https://doi.org/10.1111/j.1530-9290.2008.00004.x>.
- [228] S. Knöttner, R. Hofmann, Assessment and conceptualization of industrial energy flexibility supply in mathematical optimization in a competitive and changing environment, *Energy Convers. Manage.* 304 (2024), <https://doi.org/10.1016/j.enconman.2024.118205>.
- [229] R. Hofmann, T. Berntsson, How to use excess heat in industry? - conclusions from international networking within the IETS TCP, in: S.E.B.-M.A.M.J.J.K.M.W.B.M. W.B.A.K.N.Z.T.K.R. Elmagaard B (Ed.), *Proceedings of ECOS 2022 - 35th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, DTU Construct, 2022, pp. 1725–1732.
- [230] BMK, Integrierter österreichischer Netzinfrastrukturplan (ÖNIP), in: E. Federal Ministry Republic of Austria Climate Action, Energy, Mobility, Innovation and Technology, 2024.
- [231] EU, Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy From Renewable Sources, and Repealing Council, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L2413&qid=1699364355105>, 2023.
- [232] E. Hoxha, M. Röck, B. Truger, K. Steininger, A. Passer, Austrian GHG emission targets for new buildings and major renovations: an exploratory study, in: H.A.T. L.F.P.K.I.M.K.F.C. Wallbaum H (Ed.), *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, 2020, <https://doi.org/10.1088/1755-1315/588/3/032052>.
- [233] E. Mäki, C. Hennig, D. Thrän, N. Lange, T. Schildhauer, F. Schipfer, Defining bioenergy system services to accelerate the integration of bioenergy into a low-carbon economy, *Biofuels Bioprod. Biorefin.* 18 (4) (2024) 793–803, <https://doi.org/10.1002/bbb.2649>.
- [234] E. Mäki, C. Hennig, D. Thrän, N. Lange, T. Schildhauer, F. Schipfer, Defining the value of bioenergy system services for accelerating the integration of bioenergy into a low-carbon economy, in: S.N.G.A. Bari ID (Ed.), *European Biomass Conference and Exhibition Proceedings, ETA-Florence Renewable Energies*, 2023, pp. 363–367.
- [235] J. Baumgartner, K. Gruber, S.G. Simoes, Y.M. Saint-Drenan, J. Schmidt, Less information, similar performance: comparing machine learning-based time series of wind power generation to renewables.ninja, *Energies* 13 (9) (2020), <https://doi.org/10.3390/en13092277>.
- [236] K. Gruber, T. Gauster, G. Laaha, P. Regner, J. Schmidt, Profitability and investment risk of Texan power system winterization, *Nat. Energy* 7 (5) (2022) 409–416, <https://doi.org/10.1038/s41560-022-00994-y>.
- [237] K. Gruber, T. Gauster, G. Laaha, P. Regner, J. Schmidt, Winterizing power plants pays off for risk-neutral investors in Texas, *Nat. Energy* 7 (5) (2022) 398–399, <https://doi.org/10.1038/s41560-022-01031-8>.
- [238] W. Sebastian, R. Peter, B.M. Ulrich, S. Johannes, Inferring local social cost from renewable zoning decisions. Evidence from Lower Austria's wind power zoning, *Energy Econ.* 139 (2024) 107865, <https://doi.org/10.1016/j.eneco.2024.107865>.
- [239] K. Gruber, C. Klöckl, P. Regner, J. Baumgartner, J. Schmidt, Assessing the Global Wind Atlas and local measurements for bias correction of wind power generation simulated from MERRA-2 in Brazil, *Energy* 189 (2019), <https://doi.org/10.1016/j.energy.2019.116212>.
- [240] S. Eker, T.M. Lenton, T. Powell, J. Scheffran, S.R. Smith, D. Swamy, C. Zimm, Cross-system interactions for positive tipping cascades, *Earth Syst. Dynam.* 15 (3) (2024) 789–800, <https://doi.org/10.5194/esd-15-789-2024>.
- [241] S. Eker, C. Wilson, N. Höhne, M.S. McCaffrey, I. Monasterolo, L. Niamir, C. Zimm, Harnessing social tipping dynamics: a systems approach for accelerating decarbonization, *One Earth* 7 (6) (2024) 976–988, <https://doi.org/10.1016/j.oneear.2024.05.012>.
- [242] J.S. Kikstra, A. Vinca, F. Lovat, B. Boza-Kiss, B. van Ruijven, C. Wilson, J. Rogelj, B. Zakeri, O. Fricko, K. Riahi, Climate mitigation scenarios with persistent COVID-19-related energy demand changes, *Nat. Energy* 6 (12) (2021) 1114–1123, <https://doi.org/10.1038/s41560-021-00904-8>.
- [243] J.U. Shepard, B.J. van Ruijven, B. Zakeri, Impacts of trade friction and climate policy on global energy trade network, *Energies* 15 (17) (2022), <https://doi.org/10.3390/en15176171>.
- [244] B. Zakeri, K. Paulavets, L. Barreto-Gomez, L.G. Echeverri, S. Pachauri, B. Boza-Kiss, C. Zimm, J. Rogelj, F. Creutzig, D. Ürges-Vorsatz, D.G. Victor, M.D. Bazilian, S. Fritz, D. Gielen, D.L. McCollum, L. Srivastava, J.D. Hunt, S. Pouya, Pandemic, war, and global energy transitions, *Energies* 15 (17) (2022), <https://doi.org/10.3390/en15176114>.
- [245] M. Andrijevic, C.F. Schleussner, J. Crespo Cuarema, T. Lissner, R. Mutarak, K. Riahi, E. Theokritoff, A. Thomas, N. van Maanen, E. Byers, Towards scenario representation of adaptive capacity for global climate change assessments, *Nat. Clim. Change* 13 (8) (2023) 778–787, <https://doi.org/10.1038/s41558-023-01725-1>.
- [246] W. Steele, J. Handmer, I. McShane, *Hot Cities: A Transdisciplinary Agenda*, Edward Elgar Publishing Ltd., 2023.
- [247] A. Mastrucci, E. Byers, S. Pachauri, N. Rao, B. van Ruijven, Cooling access and energy requirements for adaptation to heat stress in megacities, *Mitig. Adapt. Strateg. Glob. Change* 27 (8) (2022), <https://doi.org/10.1007/s11027-022-10032-7>.
- [248] A.L. Argentin, T. Hauthaler, M. Liebl, J. Robl, S. Hergarten, G. Prasicek, B. Salcher, D. Hölbling, C. Pfalzner-Gibbon, L. Mandl, M. Maroschek, L. Abad, Z. Dabiri, Influence of rheology on landslide-dammed lake impoundment and sediment trapping: back-analysis of the Hintersee landslide dam, *Geomorphology* 414 (2022), <https://doi.org/10.1016/j.geomorph.2022.108363>.
- [249] S. Hanger-Kopp, T. Thaler, S. Seebauer, T. Schinko, C. Clar, Defining and operationalizing path dependency for the development and monitoring of adaptation pathways, *Glob. Environ. Chang.* 72 (2022), <https://doi.org/10.1016/j.gloenvcha.2021.102425>.
- [250] M. Hüllsiek, T. Thaler, S. Fuchs, The impact of humanitarian assistance on post-disaster social vulnerabilities: some early reflections on the Nepal earthquake in 2015, *Disasters* 45 (3) (2021) 577–603, <https://doi.org/10.1111/disa.12437>.
- [251] C. Kuhlicke, S. Seebauer, P. Hudson, C. Begg, P. Bubeck, C. Dittmer, T. Grothmann, A. Heidenreich, H. Kreibich, D.F. Lorenz, T. Masson, J. Reiter, T. Thaler, A.H. Thieken, S. Bamberg, The behavioral turn in flood risk management, its assumptions and potential implications, *WIREs Water* 7 (3) (2020), <https://doi.org/10.1002/WAT2.1418>.
- [252] M. Papathoma-Köhle, T. Thaler, S. Fuchs, An institutional approach to vulnerability: evidence from natural hazard management in Europe, *Environ. Res. Lett.* 16 (4) (2021), <https://doi.org/10.1088/1748-9326/abe88c>.
- [253] M. Rauter, A. Schindelegger, S. Fuchs, T. Thaler, Deconstructing the legal framework for flood protection in Austria: individual and state responsibilities from a planning perspective, *Water Int.* 44 (5) (2019) 571–587, <https://doi.org/10.1080/02508060.2019.1627641>.
- [254] S. Seebauer, T. Thaler, S. Hanger-Kopp, T. Schinko, How path dependency manifests in flood risk management: observations from four decades in the Enns and Aist catchments in Austria, *Reg. Environ. Chang.* 23 (1) (2023), <https://doi.org/10.1007/s11013-023-02029-y>.
- [255] T. Thaler, C. Clar, L. Junger, R. Nordbeck, Opportunities and challenges for transdisciplinary research in flood risk management: some critical reflections and lessons learnt for research on sustainability, *Eco. mont* 13 (2) (2021) 42–47, <https://doi.org/10.1553/0X003C9DA2>.
- [256] T. Thaler, S. Fuchs, Financial recovery schemes in Austria: how planned relocation is used as an answer to future flood events, *Environmental Hazards* 19 (3) (2020) 268–284, <https://doi.org/10.1080/17477891.2019.1665982>.
- [257] T. Thaler, E. Genovese, *Individual Behaviour in Disaster Risk Reduction*, Springer International Publishing, 2023.
- [258] T. Thaler, S. Hanger-Kopp, T. Schinko, R. Nordbeck, Addressing path dependencies in decision-making processes for operationalizing compound climate-risk management, *iScience* 26 (7) (2023), <https://doi.org/10.1016/j.isci.2023.107073>.
- [259] T. Thaler, S. Seebauer, A. Schindelegger, Patience, persistence and pre-signals: policy dynamics of planned relocation in Austria, *Glob. Environ. Chang.* 63 (2020), <https://doi.org/10.1016/j.gloenvcha.2020.102122>.
- [260] K. Weber, D. Damjanovic, T. Thaler, Impacts of social contracts for citizens in the austrian flood risk management system, *International Journal of Disaster Risk Reduction* 102 (2024), <https://doi.org/10.1016/j.ijdrr.2024.104266>.
- [261] R. Wyss, T. Luthé, L. Pedoth, S. Schneiderbauer, C. Adler, M. Apple, E.E. Acosta, H. Fitzpatrick, J. Haider, G. Ikizer, A.J. Imperiale, N. Karanci, E. Posch, O. Saidmamatov, T. Thaler, Mountain resilience: a systematic literature review and paths to the future, *Mt. Res. Dev.* 42 (2) (2022) A23–A36, <https://doi.org/10.1659/MRD-JOURNAL-D-21-00044.1>.
- [262] T. Thaler, E.C. Penning-Rowsell, Policy experimentation within flood risk management: transition pathways in Austria, *Geogr. J.* 189 (4) (2023) 701–714, <https://doi.org/10.1111/geoj.12528>.
- [263] J.L. Leis, S. Kienberger, Climate risk and vulnerability assessment of floods in Austria: mapping homogenous regions, hotspots and typologies, *Sustainability (Switzerland)* 12 (16) (2020), <https://doi.org/10.3390/su12166458>.
- [264] M. Zebisch, S. Schneiderbauer, K. Fritzsche, P. Bubeck, S. Kienberger, W. Kahlenborn, S. Schwan, T. Below, The vulnerability sourcebook and climate impact chains – a standardised framework for a climate vulnerability and risk assessment, *International Journal of Climate Change Strategies and Management* 13 (1) (2021) 35–59, <https://doi.org/10.1108/IJCCSM-07-2019-0042>.

- [265] T. Geiger, T. Rösli, D.N. Bresch, B. Erhardt, A.M. Fischer, D. Imgrüth, S. Kienberger, L. Mainetti, G. Mühlbacher, R. Spiekermann, How to provide actionable information on weather and climate impacts?—a summary of strategic, methodological, and technical perspectives, *Frontiers in Climate* 6 (2024), <https://doi.org/10.3389/fclim.2024.1343993>.
- [266] M. Themessl, K. Enigl, S. Reisenhofer, J. Köberl, D. Kortschak, S. Reichel, M. Ostermann, S. Kienberger, D. Tiede, D.N. Bresch, T. Rösli, D. Lehner, C. Schubert, A. Pichler, M. Leitner, M. Balas, Collection, standardization and attribution of robust disaster event information—a demonstrator of a national event-based loss and damage database in Austria, *Geosciences (Switzerland)* 12 (8) (2022), <https://doi.org/10.3390/geosciences12080283>.
- [267] L. Petutschnig, E. Rome, D. Lückerrath, K. Milde, Å. Gerger Swartling, C. Aall, M. Meyer, G. Jordá, J. Gobert, M. Englund, K. André, M. Bour, E.M.N.A.N. Attoh, B. Dale, K. Renner, A. Cauchy, S. Reuschel, F. Rudolf, M. Aguilles, C. Melo-Aguilar, M. Zebisch, S. Kienberger, Research advancements for impact chain based climate risk and vulnerability assessments, *Frontiers in Climate* 5 (2023), <https://doi.org/10.3389/fclim.2023.1095631>.
- [268] V. Streifeneder, S. Kienberger, S. Reichel, D. Höllbling, Socio-economic vulnerability assessment for supporting a sustainable pandemic management in Austria, *Sustainability (Switzerland)* 16 (1) (2024), <https://doi.org/10.3390/su16010078>.
- [269] L. Menk, T. Schinko, V. Karabaczek, I. Hagen, S. Kienberger, What's at stake? A human well-being based proposal for assessing risk of loss and damage from climate change, *Frontiers in Climate* 4 (2022), <https://doi.org/10.3389/fclim.2022.1032886>.
- [270] T. Schinko, V. Karabaczek, L. Menk, S. Kienberger, Identifying constraints and limits to climate change adaptation in Austria under deep uncertainty, *Frontiers in Climate* 6 (2024), <https://doi.org/10.3389/fclim.2024.1303767>.
- [271] K. Reiter, N. Knittel, G. Bachner, S. Hochrainer-Stigler, Barriers and ways forward to climate risk management against indirect effects of natural disasters: a case study on flood risk in Austria, *Clim. Risk Manag.* 36 (2022), <https://doi.org/10.1016/j.crm.2022.100431>.
- [272] T. Sieg, T. Schinko, K. Vogel, R. Mechler, B. Merz, H. Kreibich, Integrated assessment of short-term direct and indirect economic flood impacts including uncertainty quantification, *PLoS One* 14 (4) (2019), <https://doi.org/10.1371/journal.pone.0212932>.
- [273] G. Bachner, N. Knittel, S. Poledna, S. Hochrainer-Stigler, K. Reiter, Revealing indirect risks in complex socioeconomic systems: a highly detailed multi-model analysis of flood events in Austria, *Risk Anal.* 44 (1) (2024) 229–243, <https://doi.org/10.1111/risa.14144>.
- [274] S. Hochrainer-Stigler, G. Bachner, N. Knittel, S. Poledna, K. Reiter, F. Bosello, Risk management against indirect risks from disasters: a multi-model and participatory governance framework applied to flood risk in Austria, *International Journal of Disaster Risk Reduction* 106 (2024), <https://doi.org/10.1016/j.ijdrr.2024.104425>.
- [275] S. Hochrainer-Stigler, R. Trogrlić Šakić, K. Reiter, P.J. Ward, M.C. de Ruiter, M. J. Duncan, S. Torresan, R. Ciurean, J. Mysiak, D. Stuparu, S. Gottardo, Toward a framework for systemic multi-hazard and multi-risk assessment and management, *IScience* 26 (5) (2023), <https://doi.org/10.1016/j.isci.2023.106736>.
- [276] S. Hochrainer-Stigler, T.M. Deubelli-Hwang, J. Parviainen, L. Cumiskey, P. J. Schweizer, U. Dieckmann, Managing systemic risk through transformative change: combining systemic risk analysis with knowledge co-production, *One Earth* 7 (5) (2024) 771–781, <https://doi.org/10.1016/j.oneear.2024.04.014>.
- [277] S. Hochrainer-Stigler, T.M. Deubelli-Hwang, R. Mechler, U. Dieckmann, F. Laurien, J. Handmer, Closing the 'operationalisation gap': insights from systemic risk research to inform transformational adaptation and risk management, *Clim. Risk Manag.* 41 (2023), <https://doi.org/10.1016/j.crm.2023.100531>.
- [278] C. Colon, S. Hochrainer-Stigler, Systemic risks in supply chains: a need for system-level governance, *Supply Chain Manag.* 28 (4) (2023) 682–694, <https://doi.org/10.1108/SCM-03-2022-0101>.
- [279] S. Hochrainer-Stigler, C. Colon, G. Boza, S. Poledna, E. Rovenskaya, U. Dieckmann, Enhancing resilience of systems to individual and systemic risk: steps toward an integrative framework, *International Journal of Disaster Risk Reduction* 51 (2020), <https://doi.org/10.1016/j.ijdrr.2020.101868>.
- [280] F. Gaupp, J. Hall, S. Hochrainer-Stigler, S. Dadson, Changing risks of simultaneous global breadbasket failure, *Nat. Clim. Chang.* 10 (1) (2020) 54–57, <https://doi.org/10.1038/s41558-019-0600-z>.
- [281] S. Hochrainer-Stigler, R. Šakić Trogrlić, K. Reiter, Fiscal resilience over time and its management in the context of multi-risks: an application to the Danube Region, *Nat. Hazards* (2024), <https://doi.org/10.1007/s11069-024-06678-y>.
- [282] C. Huggel, L.M. Bouwer, S. Juhola, R. Mechler, V. Muccione, B. Orlove, I. Wallimann-Helmer, The existential risk space of climate change, *Clim. Change* 174 (1–2) (2022), <https://doi.org/10.1007/s10584-022-03430-y>.
- [283] R. Cimdins, A. Krasovskiy, F. Kraxner, Regional variability and driving forces behind forest fires in Sweden, *Remote Sens.* 14 (22) (2022), <https://doi.org/10.3390/rs14225826>.
- [284] S. Corning, A. Krasovskiy, P. Kiparisov, J. San Pedro, C.M. Viana, F. Kraxner, Anticipating future risks of climate-driven wildfires in boreal forests, *Fire* 7 (4) (2024), <https://doi.org/10.3390/Fire7040144>.
- [285] S.N. Corning, E. Boere, A. Krasovskiy, A. Lessa Derici Augustynczyk, T. Shepherd, R. Ghosh, F. Kraxner, P. Havlík, Flammable futures—storylines of climatic impacts on wildfire events and palm oil plantations in Indonesia, *Environ. Res. Lett.* 19 (11) (2024), <https://doi.org/10.1088/1748-9326/ad7bcc>.
- [286] R.A. Hammed, G.L. Alawode, L.E. Montoya, A. Krasovskiy, F. Kraxner, Exploring drivers of wildfires in Spain, *Land* 13 (6) (2024), <https://doi.org/10.3390/land13060762>.
- [287] H.W. Jo, A. Krasovskiy, M. Hong, S. Corning, W. Kim, F. Kraxner, W.K. Lee, Modeling historical and future forest fires in South Korea: the FLAM optimization approach, *Remote Sens.* 15 (5) (2023), <https://doi.org/10.3390/rs15051446>.
- [288] M. Matsala, A. Odruzhenko, T. Hinchuk, V. Myroniuk, I. Drobyshyev, S. Sydorenko, S. Zibtsev, B. Milakovskiy, D. Schepaschenko, F. Kraxner, A. Bilous, War drives forest fire risks and highlights the need for more ecologically-sound forest management in post-war Ukraine, *Sci. Rep.* 14 (1) (2024), <https://doi.org/10.1038/s41598-024-54811-5>.
- [289] V. Auer, P. Rauch, Wood supply chain risks and risk mitigation strategies: a systematic review focusing on the Northern hemisphere, *Biomass Bioenergy* 148 (2021), <https://doi.org/10.1016/j.biombioe.2021.106001>.
- [290] C. Kogler, P. Rauch, A discrete-event simulation model to test multimodal strategies for a greener and more resilient wood supply, *Can. J. For. Res.* 49 (10) (2019) 1298–1310, <https://doi.org/10.1139/cjfr-2018-0542>.
- [291] C. Kogler, P. Rauch, Lead time and quality driven transport strategies for the wood supply chain, *Res. Transp. Bus. Manag.* 47 (2023), <https://doi.org/10.1016/j.rtbm.2023.100946>.
- [292] C. Kogler, S. Schimpfhuber, C. Eichberger, P. Rauch, Benchmarking procurement cost saving strategies for wood supply chains, *Forests* 12 (8) (2021), <https://doi.org/10.3390/f12081086>.
- [293] T. Palander, T. Tokola, S.A. Borz, P. Rauch, Forest supply chains during digitalization: current implementations and prospects in near future, *Curr. For. Rep.* 10 (3) (2024) 223–238, <https://doi.org/10.1007/s40725-024-00218-4>.
- [294] A. Chakraborty, T. Reisch, C. Diem, P. Astudillo-Estévez, S. Thurner, Inequality in economic shock exposures across the global firm-level supply network, *Nat. Commun.* 15 (1) (2024), <https://doi.org/10.1038/s41467-024-46126-w>.
- [295] C. Diem, A. Borsos, T. Reisch, J. Kertész, S. Thurner, Quantifying firm-level economic systemic risk from nation-wide supply networks, *Sci. Rep.* 12 (1) (2022), <https://doi.org/10.1038/s41598-022-11522-z>.
- [296] P. Klimek, S. Thurner, The lasting effects of famine, *Science (New York, N.Y.)* 385 (6709) (2024) 606–607, <https://doi.org/10.1126/science.adr1425>.
- [297] A. Pichler, C. Diem, A. Brintrup, F. Lafond, G. Magerman, G. Buiten, T.Y. Choi, V. M. Carvalho, J.D. Farmer, S. Thurner, Building an alliance to map global supply networks, *Science* 382 (6668) (2023) 270–272, <https://doi.org/10.1126/science.adf7521>.
- [298] J. Stangl, A. Borsos, C. Diem, T. Reisch, S. Thurner, Firm-level supply chains to minimize unemployment and economic losses in rapid decarbonization scenarios, *Nat. Sustainability* 7 (5) (2024) 581–589, <https://doi.org/10.1038/s41893-024-01321-x>.
- [299] X. Yue, S. Pye, J. DeCarolis, F.G.N. Li, F. Rogan, B.Ó. Gallachóir, A review of approaches to uncertainty assessment in energy system optimization models, *Energ. Strat. Rev.* 21 (2018) 204–217, <https://doi.org/10.1016/j.esr.2018.06.003>.
- [300] A.H. van der Weijde, B.F. Hobbs, The economics of planning electricity transmission to accommodate renewables: using two-stage optimisation to evaluate flexibility and the cost of disregarding uncertainty, *Energy Econ.* 34 (6) (2012) 2089–2101, <https://doi.org/10.1016/j.eneco.2012.02.015>.
- [301] S. Collins, J.P. Deane, K. Poncelet, E. Panos, R.C. Pietzcker, E. Delarue, B. P. Ó Gallachóir, Integrating short term variations of the power system into integrated energy system models: a methodological review, *Renew. Sustain. Energy Rev.* 76 (2017) 839–856, <https://doi.org/10.1016/j.rser.2017.03.090>.
- [302] D.L. McCollum, A. Gambhir, J. Rogelj, C. Wilson, Energy modellers should explore extremes more systematically in scenarios, *Nat. Energy* 5 (2) (2020) 104–107, <https://doi.org/10.1038/s41560-020-0555-3>.
- [303] L. Kemp, C. Xu, J. Depledge, K.L. Ebi, G. Gibbins, T.A. Kohler, J. Rockström, M. Scheffer, H.J. Schellnhuber, W. Steffen, T.M. Lenton, Climate endgame: exploring catastrophic climate change scenarios, *Proc. Natl. Acad. Sci.* 119 (34) (2022) e2108146119, <https://doi.org/10.1073/pnas.2108146119>.
- [304] A. Ioannou, A. Angus, F. Brennan, Risk-based methods for sustainable energy system planning: a review, *Renew. Sustain. Energy Rev.* 74 (2017) 602–615, <https://doi.org/10.1016/j.rser.2017.02.082>.
- [305] F.A. Felder, P. Kumar, A review of existing deep decarbonization models and their potential in policymaking, *Renew. Sustain. Energy Rev.* 152 (2021), <https://doi.org/10.1016/j.rser.2021.111655>.
- [306] D. Süsser, H. Gaschnig, A. Ceglaz, V. Stavrakas, A. Flamos, J. Lilliestam, Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models, *Energy* 239 (2022), <https://doi.org/10.1016/j.energy.2021.121909>.
- [307] K.O. Yoro, M.O. Daramola, P.T. Sekoai, U.N. Wilson, O. Eterigho-Ikelegbe, Update on current approaches, challenges, and prospects of modeling and simulation in renewable and sustainable energy systems, *Renew. Sustain. Energy Rev.* 150 (2021), <https://doi.org/10.1016/j.rser.2021.111506>.
- [308] M. Kirchner, H. Mitter, U.A. Schneider, M. Sommer, K. Falkner, E. Schmid, Uncertainty concepts for integrated modeling - review and application for identifying uncertainties and uncertainty propagation pathways, *Environ. Model. Softw.* 135 (2021), <https://doi.org/10.1016/j.envsoft.2020.104905>.
- [309] BMK, Integrierter nationaler Energie- und Klimaplan für Österreich (NEKP), in: E. Federal Ministry Republic of Austria Climate Action, Energy, Mobility, Innovation and Technology, 2024.
- [310] A. Grunwald, Technology Assessment in Practice and Theory, 2018.
- [311] A. Grunwald, Parliamentary technology assessment and risk communication, *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz* 65 (5) (2022) 552–558, <https://doi.org/10.1007/s00103-022-03523-0>.

- [312] S. Salehi, Y. Zare Mehrjerdi, A. Sadegheih, H. Hosseini-Nasab, Designing a resilient and sustainable biomass supply chain network through the optimization approach under uncertainty and the disruption, *J. Clean. Prod.* 359 (2022), <https://doi.org/10.1016/j.jclepro.2022.131741>.
- [313] A. Sharifi, Y. Yamagata, Principles and criteria for assessing urban energy resilience: a literature review, *Renew. Sustain. Energy Rev.* 60 (2016) 1654–1677, <https://doi.org/10.1016/j.rser.2016.03.028>.
- [314] M.H. Spiegel, E.M.S.P. Veith, T.I. Strasser, The spectrum of proactive, resilient multi-microgrid scheduling: a systematic literature review, *Energies* 13 (17) (2020), <https://doi.org/10.3390/en13174543>.
- [315] S. Cocuccioni, F. Romagnoli, M. Pittore, I. Armas, D.T. Danila, G. Osaci, C. Albulescu, Ç. Göksu, S. Kundak, K.Y. Arslanlı, D. Kalkanlı, E.Ö. Pak, B. E. Konukçu, T. Wenzel, P. Marr, E. de Zeeuw-van Dalfsen, L. Savelberg, P. Kalubowila, M. Hürlimann, M. Bockarjova, B. Witvliet, C. van Westen, F. Atun, The use of impact chains to describe complex cause-effect relationships within a systemic multi-sectoral and multi-hazard risk assessment, in: *Lecture Notes in Civil Engineering* 401 LNCE, 2024, pp. 433–447, https://doi.org/10.1007/978-3-031-57357-6_38.
- [316] M.M. Danziger, A.-L. Barabási, Recovery coupling in multilayer networks, *Nat. Commun.* 13 (1) (2022) 955, <https://doi.org/10.1038/s41467-022-28379-5>.