Energy Research & Social Science 131 (2026) 104505

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Review

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

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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 (CO_2) 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.

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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

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 Agency[1] (IEA) in 1974 and the Intergovernmental Panel on Climate Change[2] (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 CO_2 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 Task[3] 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 CO_2 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 *bioenergy*, *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* package[6] 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*™ software[7] 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.

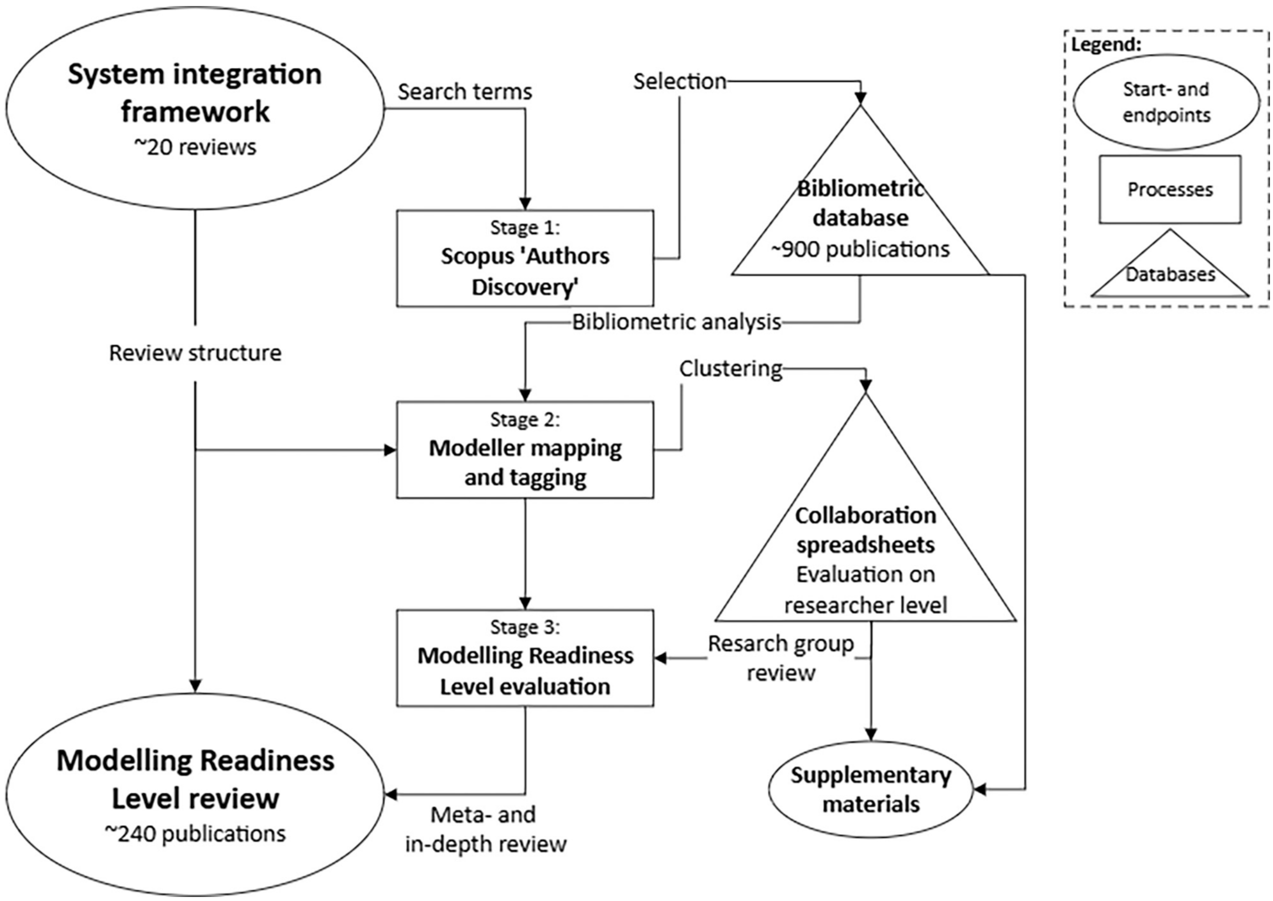

Fig. 1. Presents a flow diagram illustrating the methodology of multi-stage meta-analysis and in-depth review.
Source: own illustration.

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

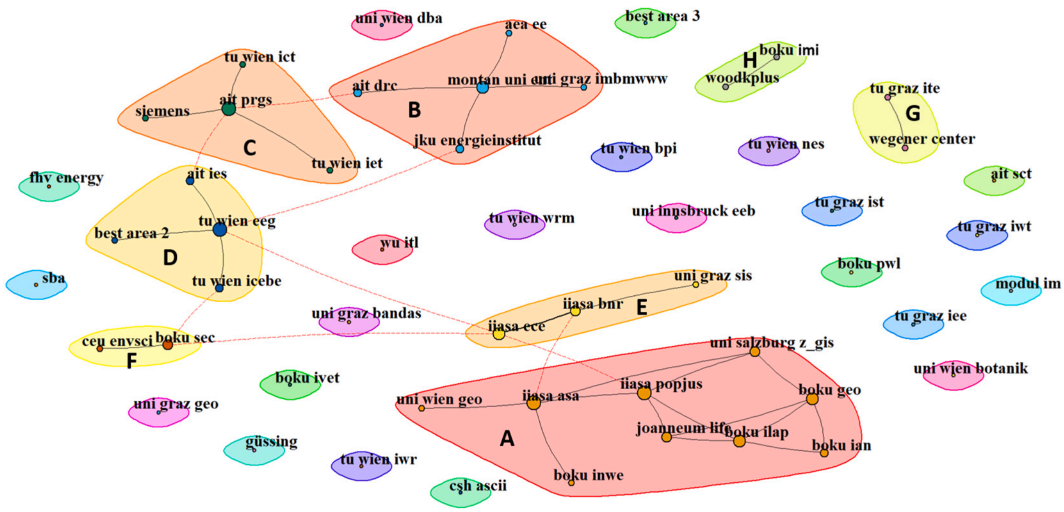

Fig. 2. Co-authorship network of Austrian research groups relevant to integrated energy system modelling.
Source: own illustration using the R Bibliometrix package.

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 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].

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	[36–51]
		TU Wien ICEBE	[52–55]
Medium	Heating network modelling	TU Wien EEG	[56–67]
		Uni Innsbruck	[68–74]
High - Medium	Electricity sector coupling	TU Graz IIE	[75–82]
		TU Wien EEG	[64,83–94]
		Boku INWE	[95–97]
		TU Wien BPI	[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	[86,92,105–121]
		TU Wien ICT	[122–127]
		TU Wien NES	[128–134]
		AIT DRC	[135,136]
Low	Multisector coupling - industry	AIT IES, Montan Uni, JKU	[137–149]
		Wegener Center	[150–153]
Low	Multisector coupling - circularity	BOKU SEC	[154–164]
		TU Wien IWR	[165–177]
		Uni Graz ITE	[178–186]
		WU Wien	[187–189]
Low	Hybrid energy systems - bioenergy	IIASA BNR	[190–207]
		BEST, TU Graz IRT	[208–215]
Low	Energy-food-water nexus	IIASA ECE, IIASA BNR	[216–226]

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 CO_2 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 CO_2 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 project[8] 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 CO_2 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 (oemof)*, operational modelling, and exergy-based optimization [147,148]. Broader European potentials for valorizing biogenic and fossil CO_2 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 CO_2 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 CO_2 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 CO_2 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]
Econosphere	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 *Considered uncertainties in ESMs*	High MRL *on global warming*	Medium MRL *on weather seasonality and day-nighttime*	Low but growing MRL *on climate extremes*
Human system *Considered uncertainties in ESMs*	High MRL *on socio-economic trends*	Medium MRL *on costs and prices, on trade*	Lowest MRL *on accidents, market crashes, wars, cyber-threats*
	Potential Energy System Modelling Evolution →		

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 Netzinfrastrukturplan (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 online[9]). 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 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 CoPilote.

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	ASCII	Supply Chain Intelligence Institute Austria	
Institute	BEST Area 2.2	Bioenergy and Sustainable Technologies GmbH	Area 2 Digital Methods and Solutions
Institute	BEST Area 3	Bioenergy and Sustainable Technologies GmbH	Area 3 Sustainable Supply and Value Cycles
University	Boku Geo	University of Natural Resources and Life Sciences	Department of Landscape, Spatial and Infrastructure Sciences
University	BOKU IAN	University of Natural Resources and Life Sciences	Department of Civil Engineering and Natural Hazards
University	BOKU IEB	University of Natural Resources and Life Sciences	Department of Agrobiotechnology
University	Boku ILAP	University of Natural Resources and Life Sciences	Department of Landscape, Spatial and Infrastructure Sciences
University	BOKU INWE	University of Natural Resources and Life Sciences	Department of Economics and Social Sciences

(continued on next page)

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, Klmatologie und Meterologie	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

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