SENTINEL

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BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE: SECURE, CLEAN AND EFFICIENT ENERGY

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Version log

Version	Date	Released by	Nature of change
0.1	30/September/2019	Philipp Thunshirn (UniGraz)	Draft review of top-down models
0.2	14/October/2019	Javier Lopez-Prol (UniGraz)	Structure and early draft of merged document
0.3	1/December/2019	Raffaele Sgarlato (HSOG)	Draft review of bottom-up models
0.4	14/January/2020	Raffaele Sgarlato (HSOG)	Finalized review of bottom-up models
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1	4/March/2020	Karl W. Steininger (UniGraz)	Final version including executive summary

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Executive summary

The energy transition is characterized by and embedded within socio-economic and techno-environmental trends, which create the necessity to analyze trade-offs as well as the potential for synergies. Due to the complexity of these transition processes and the related uncertainties, this analysis is not a straightforward endeavor resulting in a variety of modeling approaches dealing with different aspects of the transition. Bottom-up approaches are rich in detail, but the scope in terms of covered sectors and features tends to be limited. Top-down approaches are, on the other hand, less granular but foster a more comprehensive approach. These different model approaches have emerged because building an integrated model that is both highly granular and comprehensive eventually reaches limits in terms of computational tractability.

Since sector coupling will play a major role in the energy transition, the importance of detailed multi-sectoral representations is expected to increase further. We use the heat sector as a case study because the coupling potential with the electricity sector and related benefits in terms of raising the flexibility and efficacy of mitigation is found to be significant. We find that approaches used to link (bottom-up) power system models with models of the heat system are heterogenic, because of differences in the models' scope, and are an increasingly flourishing research area. By contrast, examples of linkages between (top-down) macroeconomic models and detailed representations of the heating sector are sparse.

These findings suggest the need to advance modeling approaches that allow for a detailed multi-sectoral representation. For overcoming the identified limitations of these approaches when used in stand-alone applications, we evaluate soft-linking top-down and bottom-up models to be a promising option in order to exploit and combine the strengths of individual approaches.

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Contents

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1. Introduction

Analyses of real-world energy systems reasonably start with their observation and description. A description of the energetic value chain is possible at various levels of detail. Comprehensive conceptualizations of the energetic value chain of a system include the energy service or "functionality" of energy (e.g. low-temperature heat for comfortable housing), the required satisfiers to fulfill functionalities (e.g. application technologies like radiators and related transformation technologies like gas heating) and the used primary energy source (e.g. natural gas) (Köppl and Schleicher, 2018). Due to manifold environmental and socio-economic developments, real-world energy systems and their respective value chains are continuously changing, posing challenges to system operators, users and markets.

As the first step in this review of observed trends and paradigms in modelling the economic impacts of disruptive energy supply, section 2 – under a societal and policy perspective – explores the environmental and socio-economic developments and trends relevant to the European energy system, and the challenges and trade-offs likely to be at center stage. We find that in absence of optimality (and so called "first-best" worlds), many open issues and energy transition-related research questions led to a surge in new pathway modelling approaches. Within these pathway approaches, one fundamental issue increasingly investigated relates to the potential decarbonization of the heating sector by (renewables) electrification. We thus – as a crucial exemplifying and generalizable case – focus on modeling interlinkages/coupling of power and heat sectors as a concrete example of a current critical gap and potential avenue in future energy modelling.

While section 2 sheds light on such electrification trends and related trade-offs, the respective methods to guide policy framing of these trends are reviewed in section 3: power market models and macroeconomic impact modelling of energy systems. These again are used to analyze the highlighted trade-offs and challenges. The functionalities of power market models and macroeconomic models are connected to various strengths and weaknesses, mapping them here enables to identify critical gaps that are to be closed by extending these models. Linking the extended versions of bottom-up (power and heating market) and top-down models (macroeconomic and power market models) is found to be a promising approach for supporting and guiding the economic design of energy systems.

Section 4 summarizes our key findings.

2. Trends and challenges

2.1. Socio-economic trends and policy perspective

Trends. The last two centuries embody substantial changes in the socio-economic sphere. While global population increased by a factor of eight (Roser et al., 2020), global primary energy consumption increased by a factor of more than twenty-five (Ritchie and Roser, 2020) and aggregate income by a factor of more than one-hundred (Roser, 2020). Underneath such aggregate figures is a vast number of temporally and spatially distinct developments such as

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the catching-up of low-income countries to living standards of early industrialized economies and the amplifying movement of people to live in ever closer proximity and interdependency (i.e. urbanization and globalization). Recently, we also observe transitions of many societies towards service economies (Kinfemichael, 2019; Liao, 2020), which are accompanied by on-going trends of electrification and digitalization. Productivity gains and dropping costs (Goldfarb and Tucker, 2019) are substantial drivers of these trends.

Acknowledging the achievements of the global takeoff (e.g. in defeating infectious diseases, or reducing child-mortalities to historical lows), the other side of the coin is accumulated pressure in various environmental spheres threatening "planetary boundaries" (Rockström et al., 2009) such as declining biodiversity, magnifying phosphor and nitrogen cycles and increasing net radiation and thus the earth's climate. The IPCC (2018) stresses the speed of depleting the remaining anthropogenic budget of greenhouse gases, which would be required not to exceed global temperature increases of 2°C compared to pre-industrial times. With current global emissions of around 42 Gt CO_2 per year, this budget will be exhausted in less than 26 years.

Trade-offs. Given this context, large private and public efforts have been undertaken in recent decades to explore socio-economic systems that allow remaining below environmental thresholds and within planetary boundaries, while keeping up the self-magnifying prosperity-cycle of modern industrialized economies. One salient success of such efforts is the tremendous decline in the costs of producing electricity from renewable sources such as photovoltaics (PV; Lafond et al., 2018). However, many innovations resolve existing problems but create new ones. PV is of intermittent character and a seasonally variable source of energy. Hence, it is yet unclear whether the existing trade-off between energy security – understood as combination of affordability and reliability – and sustainability can be overcome within the necessary time span. Storage and transmission technologies represent relevant complements and recently show promising developments (Schmidt et al., 2017; Alassi et al., 2019). Nevertheless, they are again subject to novel problems (e.g. recycling of battery components, scarcity of raw materials, or transmission lines as critical infrastructure in a geo-political sense).

Apart from technological fixes, the discussion of trade-offs also revolves around the "growth imperative" with the argument that an ever-increasing material throughput is unachievable in a world of finite resource endowments. In pre-industrial societies, the size of the population determined living standards. With the Enlightenment – and its subsequent effects on industrial development and income per capita growth – this nexus collapsed. While income growth is not sufficient for wellbeing, Antal and van den Bergh (2013) summarize, why it is still understood as necessity. For instance, no growth implies depressions, which in a vicious-circle-like way might deteriorate expectations and thus destabilizes market-based socio-economic systems ("recessions"). This led to the establishment of automatic stabilizers in favor of moderate growth (e.g. inflation targeting and cutting public expenditures to prevent overheating in boom phases, and reducing interest rates and increased deficit spending to stimulate the economy in times of turmoil).

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Open issues. At a single point in time, energy security – a relevant determinant of prosperity – and sustainability appear to be strictly conflicting goals. However, both spheres depend upon socio-economic and technological developments, which continuously change. Hence, zero-sum games (i.e. strict trade-offs) might dissolve after a while. The overarching question is whether the rate and direction of these socio-economic and technological developments can be influenced by policy in a sufficient way to reach synergies, before tapping into the mentioned area of conflicts. A pivotal economic instrument for steering such developments is to put an explicit price on external effects (e.g. greenhouse gas emissions) in order to internalize social costs (e.g. climate change impacts) that otherwise are not reflected in market prices. In economic theory, such an internalization via price signals (e.g. taxation) is among the most efficient instruments to reach a social optimum, in which economic agents behave according to changed relative prices within the given social and technological structures. On top, changed relative prices incentivize social and technological innovation affecting structural evolution.

Optimality and the social costs of carbon. Deriving the "true" value of the social costs of greenhouse gases in the real world – based on expected marginal damages (Nordhaus, 2017) – is highly contested (Pindyck, 2017; van den Bergh and Botzen, 2015; Pezzey, 2019). This approach also proved to be at the mercy of political leaders, who can defend low mitigation efforts by applying high discount rates to marginalize expected future damages relative to current benefits – as has been the case recently in the United States[1]. As alternative, some researchers call for and follow pathway approaches taking into account most recent socio-economic and technological advances for assessing optimal policy mixes in second-best settings. These kind of studies (e.g. Mayer et al., 2019; Dai et al., 2019) include but are not restricted to the analysis of "optimal" prices on emissions of greenhouse gases. They go much beyond, and focus on consequences of pathways, which are targeted to meet a combination of societal objectives (such as the well below 2° C target of the Paris Agreement simultaneously with increasing levels of well-being).

Desired future and pathways. Back-casting methods have shown to be useful tools in order to reflect on necessary milestones for reaching societal objectives (i.e. desired futures). Quantitative research increasingly signaled harmonization requirements of such "thinking-about-the-future" exercises. Since recently, a large body of research activities devotes substantial efforts to construct anchoring points for harmonization – the respective narratives are coined *shared socio-economic pathways* (SSPs; O'Neill et al., 2014; O'Neill et al., 2017). These pathways define *challenges to adaptation* and *challenges to mitigation,* which are described by very broad and plausible but distinct trends in the socio-economic system.

Context and case studies. Finally, we can also learn from a broad set of case studies. For example, looking at the decarbonization and sector-coupling of iron and steel production and electricity generation (for the case of Austria), Bachner et al. (2018) can be considered to represent a good-practice case because it identifies desired futures and respective pathways

[1] https://www.nytimes.com/2018/08/23/climate/social-cost-carbon.html

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by means including extensive stakeholder engagement. The authors show that knowledge of stakeholders, decision makers and scientists for each group in its own is incomplete, and the transdisciplinary setting followed (and deploying qualitative and quantitative methods) helped to reveal this issue. However, while some generalization of insights gained through the analysis of a specific case study will usually be possible, these will not be able to answer all questions – or for all contexts. In this context it has to be acknowledged, however, that political economy considerations (e.g. vested interests, hidden geo-political agendas, power relations, etc.) are crucially relevant - also for the specific case of the energy transition (e.g. Chang and Berdiev, 2011; Scholten and Bosman, 2016; IRENA (2019) report on "*A new world: The geopolitics of the energy transformation*").

2.2. Challenges for future modelling

In the ongoing and expected energy transition, electricity plays a major role. Most sectors, including heat, mobility, and the industry sector will increasingly become electrified. Thus, interlinkages between in particular the electricity sector and other sectors need to be analyzed to better understand the implications of these interlinkages on the power system and ultimately their wider effects on emissions of greenhouse gases and socio-economic development. For four reasons, we focus on the issue of electricity-heat linking in the remainder of this deliverable: (i) the linkage is already pronounced in today's energy system, (ii) it has large potentials in terms of energy supply, (iii) the available technologies are relatively clearly defined (cf. Appendix A) and (iv) the literature on power-heat-linkages is rich when compared to other power-to-x-linkages. For complementary analysis we refer to individual case studies for linking electricity with the mobility (Schäfer and Jacoby, 2005; Luca de Tena and Pregger, 2018) and industry sector (Lechtenböhmer, et al., 2016; Bachner et al., 2018).

Links between heat and electricity. Power and heat sectors are currently linked through the cogeneration of heat and electricity and the generation of heat using electricity. Cogeneration in combined heat and power plants (CHP) strongly affects both sectors; the obligation to supply heat can, for example, force plants to generate electricity during times of low or negative prices, inflating carbon emissions. In countries such as Denmark, Latvia or Finland up to 40% of electricity demand is served by CHP plants (Eurostat, 2017). On the other hand, the generation of heat through direct electrical heating and heat pumps significantly increases the electricity demand. A prominent example is France, where electricity-based heating of space and water accounts for 40% of the residential electricity demand (RTE, 2019).

Increasing relevance of the heat-electricity link. With increasing power market penetration of renewable energy sources, the interaction of power and heat systems is likely to become tighter and its modelling becomes more important. The main reason for this is the need for decarbonization. Most renewable energy sources (such and wind power or solar PV) directly produce electricity without the co-generation of heat. A successful transition of the heat sector will therefore, at least partly, rely on an increasing electrification (next to a more efficient low-energy building stock). The replacement of other heat sources, such as oil or

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natural gas, will drive up electricity demand but also alter its pattern; for instance, electrifying the heating sector will increase power demand more in winter than in summer. This increased seasonal variability in the electricity demand will pose significant challenges to the power sector. On the other hand, electrifying the heat sector may provide cost-efficient flexibility to the power sector, for example through comparatively cheap storage and thermal inertia. This can help integrating higher shares of variable renewable energy sources.

3. Multi-sectoral modeling

Taking stock from a review of methods relevant for assessing the long-term low-carbon transformation (Schinko et al., 2017), most identified challenges of multi-sectoral modelling can be addressed by linking/combining different methods. Challenges refer to:

- addressing disruptive/non-linear technological change,
- incorporating technological detail,
- integrating the energy cascade,
- accounting for the difference between structures and mechanisms,
- including stock-flow interactions,
- covering institutions and behavioral mechanisms,
- dealing with out of equilibrium situations and
- reflecting critically on risk and uncertainty.

Accounting for all of these challenges is an extensive research agenda. We do not claim to cover all of these challenges here but rather focus on the recent modelling trend of linking individual models. First, we provide a separate discussion of two different angles one can take in order to analyze energy-related research questions (section 3.1). For both angles (bottom-up in section 3.2 and top-down in section 3.3), we give a review of existing models and related applications, with particular on the question how the power-heat link is currently addressed. A promising trend is to integrate (or link) methods of both angles, which is discussed in section 3.4.

3.1. Modelling perspective

Complexity & uncertainty. The prime objective of modelling is to build a purposeful, simplified representation of reality (Starfield et al., 1993) that enables the modeler to perform analysis of mechanisms that help to explain and understand real-world phenomena. The reality is *complex*; hence, it is often a tedious task to separate irrelevant from relevant mechanisms, which creates *uncertainty*. The research community approaches both issues by taking stock of a diverse set of methodologies. A useful classification of such methodologies is to distinguish a bottom-up and top-down view when exploring real-world phenomena. These views co-determine which mechanisms are explored with greater resolution (to the detriment of other mechanisms) in order to tune the model to answer a specific research question.

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For instance, decision makers could be interested in the socio-economic consequences of renewable energy penetration and the related effects on electricity prices as well as economy-wide employment. Taking a bottom-up view, models like EMMA (Hirth, 2013) emphasize the relevance of technological peculiarities, such as the seasonal variability of PV and wind power, for assessing impacts on wholesale electricity prices and can give detailed answers on possible price effects. Adopting a top-down view, models such as WEGDYN (Bachner et al., 2019) emphasize the relevance of economy-wide feedback effects and can provide insights into e.g. the interaction of the electricity mix and employment effects as well as further indirect effects on the wider economy. Depending upon the research question, the integration of both approaches can be of great value. Ringkjøb et al. (2018) give a broad overview about existing idiosyncratic and hybrid models for assessing energy-related issues.

Inter- and Transdisciplinary embedding. However, by imposing conditions of optimality from a bottom-up, top-down or integrated view (e.g. least-cost, utility maximization), these models (often) lack other (e.g. contextual) factors. For instance, political economy considerations can reveal limits of real-world relative price changes. Strong opposition of the "gilets jaunes" movements in France against raising fossil fuel taxes is a delicate example for the importance of such considerations. *Inter- and Transdisciplinary embedding* can capture such phenomena through qualitative methods such as multi-criteria analysis or stakeholder engagement. Using quantitative and qualitative methods, Bachner et al. (2018) show that stakeholders might overestimate risks of decarbonization (e.g. job losses, or excess demand for electricity), when they neglect macroeconomic repercussions or interactions.

Transparency. Interdisciplinary research requires a common understanding of real-world phenomena, of the underlying mechanisms and whether and if, how models capture them. *Transparency* is not only relevant for replication exercises and validating research results but for communication within and across modelling communities (e.g. between bottom-up and top-down modelers) and with stakeholders. The current scientific framework might be a barrier to walk along the avenue of pathways modelling in an interdisciplinary and transparent way. For instance, input data of some models are connected to licenses or commercial sensitivity. Fear of losing competitive advantage can also dis-incentivize high transparency standards (Pfenninger et al., 2018).

3.1.1. Angle 1 – Bottom up

Bottom up models are detailed models that specialize on one sector (in this case the power sector). Sector coupling is captured by extending the model with another sector (through hard- or soft-linkage, see section 3.4). The strengths of bottom up power system models are specifically their ability to reflect the high temporal (and sometimes spatial) resolution necessary for modeling high shares of renewable energy sources. In contrast, heat models may have lower temporal resolutions (and therefore lower calculation times), because of higher time lags in the heat sector.

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The usage of power system models has constantly increased over the last years. To an increasing extent, the heat-electricity linkage is represented in these models. **Error! Reference source not found.** shows how scientific literature progressively uses and develops power system models (black bars). Also, developing power system models featuring the heating sector increased substantially in the last decade from 10% in 2009 to 16% in 2018 (**Error! Reference source not found.**). We present a review of linking power and heat sector models in section 3.3.

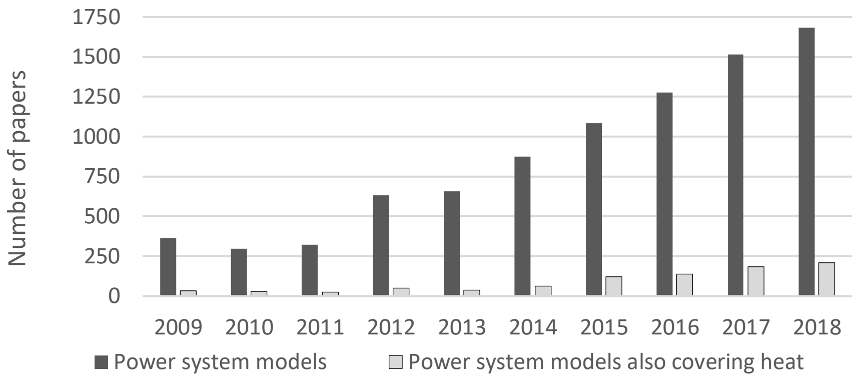

Figure 1: Papers on power system models with and without heat (as of 15.11.2019). Power system modeling becomes increasingly relevant and the number of models that include heat demand rises continuously. Quantitative literature review based on a key-word search in titles and abstracts in the Web-of-Science.[2]

3.1.2. Angle 2 – Top down

Bottom-up models have their strengths in a detailed description of energy supply given specific temporal and spatial patterns of demand. A more comprehensive but less detailed approach acknowledges circular causation; demand side responses are not exogenous but subject to economic feedbacks and rebounds. Furthermore, macroeconomic models account for structural embedding of the energetic value chain in (inter)national relations of many producing sectors and many consuming agents.

We conducted a query on quantitative analyses of power and heat issues from a macroeconomic perspective. Using a specific combination of search terms[3] in the Web-of-Science publication database, we extract 81 individual papers.[4] After manual selection based on abstracts content, we investigate 52 papers of this sample, with 5 of them published in the

[2] We used the following keywords for the analysis:
Power system models: ("electricity system" *or* "power system") *and* "model" *and* "energy"
Power system models that include heating: („electricity system" *or* „power system") *and* "model" *and* "energy" *and* („sector coupling" *or* "integrated energy system" or "heat")

[3] We used the following keywords for the query:
TOPIC: (macroeconomic AND model AND energy AND (electricity OR power OR heat*))
Refined by: WEB OF SCIENCE CATEGORIES: (ECONOMICS)
Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan=All years

[4] Note that we do not claim completeness.

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period 1993-2002, 15 papers in 2003-2012 and 32 papers in 2013-2019. A list of our selected sample can be found in Table A. 2 of Appendix C.

As can be seen in **Error! Reference source not found.**, the majority of papers focuses on electricity or power – heat is a rather underexplored topic. Bottom-up and top-down approaches are mentioned almost the same number of times. Computable general equilibrium (CGE) models seem to be the main analysis tools in this field. We refer to Faehn et al. (2020) who provide a recent review on how CGE models deal with key energy and emission trends. A rather novel approach is to compare the insights provided by different macroeconomic model families in order to reflect on outcomes and interpretations that can be contradictory (see Mercure et al., 2019 for a theoretical discussion of the difference between CGE and econometric methods and Bachner et al., 2020, for an application). However, next to these macroeconomic workhorse methods, also further relevant models exist (e.g. System Dynamic and agent-based models) which have the potential to contribute substantially to this strand of research (Schinko et al., 2017).

Table 1: Web-of-Science literature query for macroeconomic assessments of power and heat issues (as of 30.01.2020).

Category	Sub-category	Count	Category	Sub-category	Count
Topic	Energy	48	**Method**	CGE	33
	Electricity or Power	46		Econometric	10
	Heat	5		IAM	1
Approach	Bottom-up	9		Input-output	6
	Top-down	8		System dynamic	4
	Hybrid	6		Agent-based	1

3.2. Review of bottom-up models: The coupling of power and heat sectors

This section reviews the implementation of linking power and heat system models. More precisely, we focus on the interface between power and heat supply in models (in contrast to the review of entire models). We aim to give a structured overview on elements and approaches in the integrated modeling of the electricity and heat sector. To do so, we first review literature on how the interaction between heat and power has been accounted for in power system models. The 35 reviewed papers are classified in Appendix B. We find that the papers reviewed apply highly diverse modeling approaches. Fundamental differences result from the representation of dispatch and investment decisions and from the pronounced difference between central and decentral heat supply. Integrated electricity and heat models optimize installed capacities and their operation (dispatch). The representation of investments and dispatch differs between models: both can either be exogenous to the model (they are part of the model inputs) or endogenous (they are calculated by the model and are, thus, parts of the model output). This degree of endogeneity impacts the ability of models to capture the interaction between sectors and is discussed in section 3.2.1. A second profound difference between models stems from the structure of heat supply. Whilst being fundamentally different, both centralized and decentralized heating are relevant to the electricity and heat sector integration and are treated in section 3.2.2. Finally, some features are only implemented in some cases depending on the model's focus. For instance, some models feature a representation of the heating network, and apply features like uncertainty and combined operation of more than one unit. These features are described in section 3.2.3. All of the mentioned challenges are subject to data availability issues (section 3.2.4).

3.2.1. Optimization of dispatch and investment

Two fundamental approaches. The ability of an integrated model to capture the interlinkage between sectors depends on its ability to endogenously adapt to changes in either of the sectors. For example, a higher penetration of variable renewable energy (VRE) might translate into a more pronounced buildout of electric heaters.[5] Additional electric boiler capacities might also allow for supplementary buildout of VRE. Such an interlinkage is accurately captured only if a model endogenously calculates dispatch of and investments in electric boilers and renewable energy sources . Generally, models that have endogenous investments also endogenously calculate the dispatch because altering the capacities directly affects dispatch decisions. Accordingly, we have identified: (i) approaches that calculate the dispatch of units but not the optimal investment decisions and (ii) approaches that optimize both dispatch and investment.

Endogeneity of model components. In integrated models, endogeneity varies between time series analysis without optimization, dispatch and, potentially, investment optimization. For example, a model might calculate heat demand using temperature time series and, at the same time, calculate the optimal dispatch and investment into generation units. Pure time series analyses, which do not calculate investment nor dispatch, exist as well. This approach uses historical series to derive new series or indicators. For example, a pure time series can be used to estimate the theoretical and the technical potential of power-to-heat technologies based on hourly residual power demand and hourly heat demand data (Böttger et al., 2014). Nevertheless, because pure time series analyses can consist of straight forward calculations and because they are rare in this strand of literature, we do not elaborate on this approach.

Endogenous dispatch

Description. Endogenous dispatch means that the operation of each unit is determined by the model and is, thus, part of the model's output. This implies that units relevant to the integration of electricity and heat sector dispatch considering constraints of both the electricity and the heat sector. For example, a power-to-heat unit accounts for the cost of the electricity consumed and the value of the supplied heat.

How to model dispatch. The dispatch can be defined by a set of rules or by an objective function. The latter is more common as large-scale electricity market models are mostly set up as optimization models that minimize system costs (Ravn et al., 2001) or maximize welfare (Leuthold et al., 2012). Adding constraints on the heat supply (i.e. the heat supply must meet the heat demand at any point in time) will cause the heat generation units to dispatch in order

[5] Because higher VRE penetration increases the number of hours with low electricity prices, operating an electric boiler becomes more profitable

to meet the heat demand whilst preserving the optimality conditions defined by the objective function (Bach et al., 2016). However, using other ad-hoc objective functions to calculate the dispatch is possible; for example, minimizing the fluctuation of net power demand can be used to investigate the synergies between power-to-heat units[6] and wind generation (Chen et al., 2014). In a liberalized market, the dispatch based on system costs seems more realistic than a dispatch based on net power demand fluctuations. Nevertheless, an objective function for the heat supply which is only a function of heat generation units can allow for an integration without substantially increasing the model's complexity (see soft-linking in section 3.4). In this example, the electricity demand caused by the heat supply could be calculated independently of the electricity market (and used as an input for the electricity market model). To some extent, this simplistic approach would have similarities to the "peak-shaving" approach used to compute the dispatch of hydropower units (Borenstein and Bushnell, 1999).

Endogenous investment

Description. An endogenous investment model allows for the inclusion of new generation units. In most cases, this can be any type; sometimes investment is constrained to certain technologies, e.g. CHP and power-to-heat capacities.

How to model investment. Like the dispatch, also the investment policy is then defined by the model's objective function. The generation of units is constrained by their installed capacity. Additional investments result in an increase of this capacity and thus relax this constraint. If the objective function is the minimization of system cost, then the optimal investment is defined by the tradeoff between the system cost reduction derived from relaxation of the constraint and the investment costs that add to the total system cost (Münster et al., 2012). The choice of the objective function may vary depending on the market and the focus of the model. For example, social benefit[7] might be used as an objective function to maximize as well (Liu et al., 2016). Nevertheless, such an approach is not fundamentally different than a cost minimization model where the environmental cost is internalized with a price on carbon emission.

3.2.2. Centralized vs. decentralized supply

Intro. Heat supply can be organized in a central or decentral manner. We refer to decentralized heating systems as those that supply space heat and hot water to individual houses, apartments, and commercial buildings. We refer to centralized heating as systems that supply blocks or districts of multiple buildings via a heat network (Figure 2). In this section, we discuss how investment and dispatch of these two types of heating systems can be characterized and modeled.

[6] These include either a heat pump or conventional resistance heating paired with a heat storage

[7] Social benefit can be defined as the economic benefit (as with electric boilers more wind generation can be accommodate and less coal is consumed) plus the environmental benefit minus the fixed investment costs

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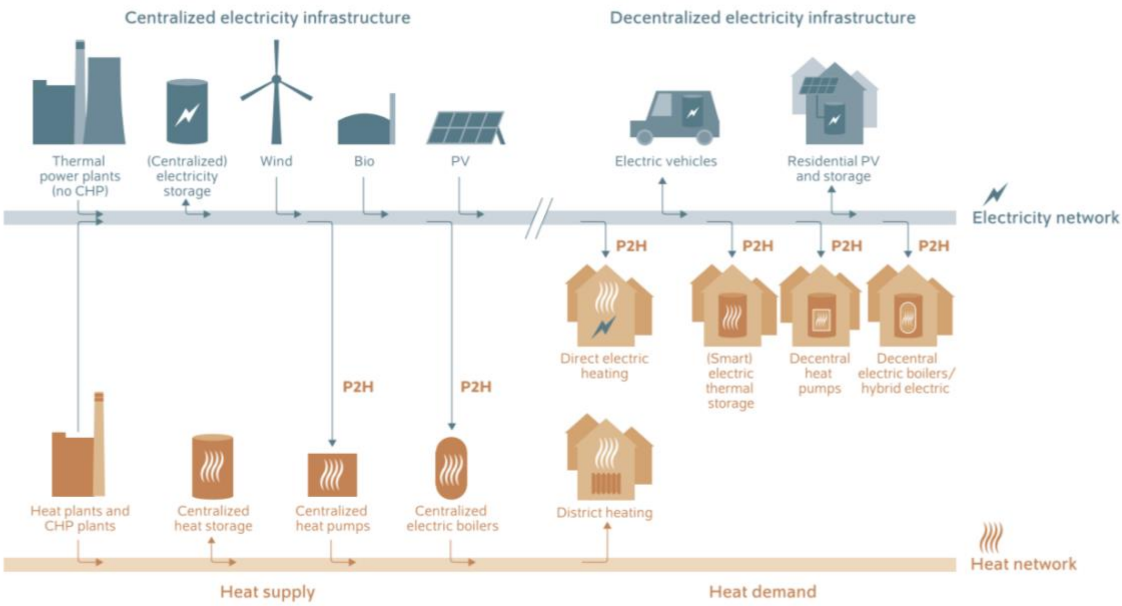

Figure 2: Interconnections of power-to-heat options with electricity and district heating networks (Bloess, 2018).

Decentral heat supply

Main characteristics. The choice of technology in decentralized heating appliances mostly depends on fuel prices, including electricity prices for the case of electric heating systems. A lower electricity price will favor the diffusion of electric heat pumps and boilers, and vice versa because electric and combustible fuel-based systems compete against each other. The decision on decentralized heating systems is often exclusive in the sense that usually one technology is selected for a heating system. Exceptions are complementary solar thermal systems and electric heat pumps with electric back-up heaters. The heating system must be dimensioned such that it is able to supply the individual heating profile, including peak demand. Thus, it is the individual building characteristics that determine the optimal choice of technology. The decision on the heating system comprises the decision on whether to connect to a heating network, if available, and is closely linked to the decision on investing in building insulation.

Implementation. In the studies we reviewed, investment in decentralized heating system is often exogenous to the model. Thus, models do not capture the influence of electricity prices on the choice of electric heating technologies. Notable exceptions are Hedegaard and Balyk (2013) and Fehrenbach et al. (2014). Their models include several building archetypes of different thermal characteristics, including the age of construction, insulation standards and the heat capacity of buildings. The investment decision on heating systems is optimized for each of these building archetypes in parallel. Dispatch decisions of decentralized electric heating systems are traditionally uncoupled from the electricity market. They are operated as locally required by the heat demand (heat-led operation). One prominent exception from this paradigm are night storage heaters; those use electricity at night to generate heat, which is stored to satisfy heat demand during the day. This fixed diurnal dispatch pattern was optimized with respect to traditional, periodic price patterns at the electricity market. Today, smart grid technologies enable a short- to real-time coupling of electric heating to electricity markets, to complement variable renewable energy sources. The building structure and hot water tanks are additional and intrinsic sources of flexibility.

Many studies examine the implications of a system-friendly dispatch of electric heating systems. Two approaches can be distinguished. Most common are mathematical optimization methods, where the dispatch of the decentral heating system is a decision variable (e.g. Arteconi et al., 2016; Fehrenbach et al., 2014; Hedegaard and Balyk, 2013; Kirkerud et al., 2014a; Patteeuw et al., 2015; Ruhnau et al., 2019b). Less frequent are heuristic methods (e.g. Barton et al., 2013; Cooper et al., 2016).

Central heat supply

Main characteristics. We refer to centralized heat system as collective heating systems that supply heat to building blocks or city districts. In contrast to decentralized heat systems, central systems include some form of network to distribute the heat. A description of the implementation of heat networks is presented in section 3.4. The necessity for heat networks implies some significantly different properties. First, a centralized heat system is characterized by higher inertia, because heat networks serve as additional heat storage and individual demand peaks smoothen with aggregation. Second, larger and various types of generators are usually installed, whereas decentralized systems tend to have only a single heat source. Last, heat networks usually come along with significant network losses that range between 1% and more than 20% of the transported heat (Li et al., 2016; Vesterlund et al., 2013). We find that not all reviewed models that include centralized heating explicitly represent heat networks.

Implementation. Investment in centralized heat technologies is more often modeled endogenously than investments in decentralized systems. To do so, most optimization models include additional equations and constraints to meet heat demand. A fundamental distinction can be made between models that only allow investment in heat supply within existing networks (which may be rising due to increasing demand or replacement of aging plants) and models that also endogenously invest in heating networks. The latter category, which is more complex, rarely occurs in the reviewed literature (Münster et al., 2012). Often, centralized heat systems comprise of multiple heat generators, using several technologies with different characteristics, e.g. multiple CHP plants and heat-only boilers. This variety of heat sources increases the flexibility in dispatch decisions. The individual peaks smoothen with aggregation (higher full load hours / utilization). There is flexibility with the networks, multiple generators, and with existing or new storages (large, central assets are easier to access), which allows a lower temporal resolution in dispatch modeling. Hard-linked models may not be able to benefit of a lower time resolution in this sector, as the electricity sector still needs to be modeled in higher time resolution (see section 3.4).

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3.2.3. Additional Features

Intro. Models can be extended with additional features. We provide additional information of implementation of combined units, uncertainty in generation and demand and heat networks in the following.

Combined units

Scoping. In this review refer to standalone units as all generators (including power-to-heat) that are not paired with other units. This is the case for units that feed into the transmission or the distribution grid or directly supply end consumers. On the other hand, we describe as combined units those units which directly interact with other units.

Depending on whether a unit is combined with other units, the impact on the behavior can be substantial when synergies between the units can be exploited. For example, a heat pump may use the flue gases of a CHP units as heat source in order to achieve a higher COP. The combined dispatch should consider and exploit this synergy. Such a combination tends to translate into a more complex set of constraints. A combination found to translate into substantial technical synergies it the one comprising a CHP unit and power-to-heart unit (especially when also paired with a heat storage) (Blarke, 2012).

Uncertainty

Most reviewed models use deterministic optimization models. These approaches reflect the behavior of units which act under perfect foresight. This is not realistic as many uncertainties affect the behavior of units. For example, renewable generation forecasts are affected by forecast errors (uncertainty in the short term), the cost decline of renewables might decelerate or not (uncertainty in the long term) or a regulatory intervention might materialize or not (potentially both, short and long term).

Perfect foresight implies that the model overestimates the information available at the point in time when a decision is taken. The less is known at the point in time of taking a decision, the less representative is a decision modeled under the assumption of perfect foresight. This depends on the stochasticity of underlying processes as wells as on the point in time when a decision is taken compared to the point in time when the information is available. For example, depending on the market design, CHP units might have to plan their heat and power generation before the day-ahead power prices are disclosed. This introduces substantial uncertainty that is best analyzed with a stochastic rather than a deterministic model. With such a setup, combining a CHP plant with an electric boiler or a heat pumps can increase the operational flexibility and, thus, the ability to schedule production under uncertainty (Nielsen et al., 2016).

Heat networks

Relevance of heat networks. Heat networks are used to transport and distribute heat in district and block heating systems. They impact the behavior of the market because they impose constraints on how much heat can be supplied to each specific node. Unlike electricity grids, only a fraction of the heat consumed within a country flows through this heat network and decentral heating networks are generally not interconnected. Because of this spatial granularity play a major role as the location defined whether network heat is available or not.

Implementation. The mathematical representation of heat networks can be compared to the representation of electricity grids with the difference that heat flows can be directed (in contrast to power flows that following Kirchhoff's laws).

Temperature levels. In practice, the water temperature in heating networks varies strongly depending on its application (see Appendix A). Also, temperature levels of the heat network vary throughout the year (they are usually lower in summer times than in winter); often these temperature differences are not represented in models. Standalone heat pumps[8] may be used to uplift the temperature from the heat source temperature to the forward temperature of a district heating network. The COP deteriorates when heat pumps bridge a high temperature difference; therefore, heat pumps are better suited to low-temperature heat distribution networks. On the other hand, feeding into the high-temperature heat transmission network has the advantage of serving a larger demand base. This tradeoff is analyzed by Bach et al. which expand the Balmorel model by time and networks dependent efficiencies and COPs. This allows to employ COPs, which are assessed ex-ante and therefore account for the temperature difference between heat source and heat sink (i.e. distribution or transmission network) (Bach et al., 2016)

Investment. Heat flow between nodes of the heating network are constrained by the capacity of the pipes. Like for other installed capacities, is it possible to calculate the optimal network expansions i.e. the expansions where the reduction of system costs offsets the additional investment costs (Münster et al., 2012). Nevertheless, this is rarely featured by the integrated models inter alia because of the data availability issue (see section 3.2.4)

3.2.4. Data availability

Open energy data. Even though transparency and reproducibility are desirable for science and policy advice, energy research lags behind in terms of open data and modeling (Pfenninger et al., 2017). While advances have been made in the mature field of power system modeling, the lack of open data is still more relevant for the emerging modeling of heat-electricity linkages.

CHP characteristics. Concerning data on existing power plants, there are now open source databases, containing some general characteristics (age, location, fuel, technology) and the electric capacity (Gotzens et al., 2019; Wiese et al., 2019). However, these databases lack more detailed information on heat-related characteristics of CHP, such as the power-to-heat ratio and the power loss coefficient of extraction-condensing turbines. Such parameters are hardly available but essential for good modeling.

[8] Heat pumps which are not part of a system comprising other units such as CHP plants or storages

Heat demand time series. Unlike electricity, heat is mostly produced by decentral systems, which are not interconnected. As a result, heat is not centrally monitored and there is no complete official publication of demand time series. Otherwise, the methodology for modelling heat demand is scattered (see Appendix A) and there are few open datasets with modeled time series (Pezzutto et al., 2019; Ruhnau et al., 2019a; Heitkoetter et al., 2020). Concerning centralized district heating, measurements are available for some networks and these can be used to estimate the missing data of the remaining networks – by exploiting the correlation to the ambient temperature and scaling to yearly heat demand date (Böttger et al., 2014). Furthermore, some works, which are based on the Danish case study, use an accurate representation of the heat transmission and distribution network (Bach et al., 2016; Münster et al., 2012) and benefit for previous data-focused studies (e.g. Möller, 2003).

3.3. Review of top down-models: macroeconomic models with endogenous power and heat demand

Relevant indicators derived from top-down macroeconomic models include distributional impacts for expenditures and disposable income of private household groups, gross domestic product and a related decomposition, terms of trade effects, wellbeing measures in terms of consumption possibilities, implications for public budgets and unemployment as well as sectoral price and quantity effects. Next to the provision of this broad set of relevant economic impact indicators, the main advantage over bottom-up models of power and heat is that macroeconomic models include endogenous demand for power and heat. In the following, we focus on the functionality of multi-sector, multi-region macroeconomic models developed for *exploring* long-run scenarios.[9] Similar to section 3.2 on bottom-up models, we here give brief model explanations and an overview of respective strengths and weaknesses of such top-down models.

Macroeconomic identities. A macroeconomic model deals – in explicit or implicit ways – with accounting identities, which consist of (i) current accounts, (ii) capital accounts, (iii) financial accounts and (iv) balance sheets. All of them give a detailed picture of the fact that expenditure flows of one economic agent are mirrored by flows of income to another. For instance, the current account contains empirical observation of the flows that workers receive as wages for supplying labor input to firms, while capitalists (i.e. firm owners) receive capital rents for supplying capital and land/resource owners receive yields for supplying land/resources (income account). In turn, firms produce goods and services by combining factors of production (i.e. labor, capital, resources, land) with intermediate inputs from other firms and supply them to markets (production account). Domestic and foreign demand for goods and services differentiates between intermediate demand by other firms and final demand of private and public agents (expenditure account), which further distinguishes current and future consumption (i.e. savings). The capital account complements these real flows of "goods and services" with flows of non-financial assets (net borrowing/lending).

[9] We refrain here from models that are better suited for *predicting* short-term developments.

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Real economic flows. Adopting the input-output structure of current account and capital account data, which reflect real economic flows (i.e. output quantities or working hours in monetary terms), is a central feature of all macroeconomic models. This structure is relevant for assessing feedback effects of the energy-economy nexus. The chosen sectoral/regional resolution and household decomposition depends on the specific research question. Models differ in the way they incorporate (im)perfect competition, economies of scale and input flexibility, particularly inter-fuel substitution possibilities. Regarding input flexibility, input-output (IO) models assume a fixed structure by tracing back real changes in quantitative flows of inputs and factors in response to exogenous policy shocks. By contrast, computable general equilibrium (CGE) models and econometric input-output (EIO) models[10] allow for input and factor substitution mechanisms calibrated to estimated elasticities. For these two model classes, the evolution of relative prices – in response to policy shocks – (co-)determine structural adjustments. The degree of price responsiveness varies between CGE and EIO models. Perfectly flexible prices (due to complete cost-pass-through) is a default assumption in CGE models, whereas price stickiness and delayed adjustment towards a long-run steady state is default in EIO models. Hence, in terms of price responsiveness, IO models and CGE models represent two ends of the same spectrum with EIO models constituting an intermediate case.

Financial flows. A further crucial distinction for these model classes is whether and how they include the financial side of the economy through the inclusion of financial accounts and balance sheets. For IO and CGE models, the default assumption is "money neutrality". The economy is assumed to be in a boom phase, thus raising aggregate demand through financial stimuli (e.g. "cheap loans") is ineffective because order books are full and production is at its full potential. Hence, the consequences of additional demand stimuli (e.g. investments) are either increased price levels ("overheating") or private households running into debt vis-à-vis the government, the rest of the world or future households. There are IO and CGE studies that account for financial flows (e.g. Aray et al., 2017; Lieu et al., 2015). However, these models only extend the ability of economic actors to finance projects by an additional channel (i.e. balance sheet of private banks) but do not capture output gaps that can be brought back to their full potential through financial stimuli. By contrast, IEO models implicitly acknowledge money-creation of private banks affecting output that does not need be at its full potential (Pollitt and Mercure et al., 2018). This is especially relevant for economies, which are in a depressive phase of a business cycle. Choosing the right model is thus case-specific, context-dependent and a crucial information when communicating results of empirical analysis (Bachner et al., 2020).

Focus on market-based mechanism. The relative price mechanism on input markets and primary factor markets (i.e. labor and capital) is essential in these top-down models.[11] Non-

[10] Note that EIO models are either New Keynesian or Post-Keynesian models, which relates to different theoretical explanations of the causes of price rigidity (Melmies, 2010).

[11] To be specific, there are only implicit prices in IO models. The main mechanism is a change in technological coefficients with constant relative prices.

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market mechanisms (e.g. climate change impacts, or health impacts)[12] and technological change (e.g. efficiency improvements, or factor productivity changes) are specified outside models; they are either introduced as exogenous shocks (in the case of CGE and IO models) or driven by estimated structural equations based on time series data (in the case of EIO). Emergent behavior (e.g. induced technological change) is not possible within the framework of these models ("how does it happen?") because they are either deterministic (IO and CGE) or the model converges towards long-run steady states even in the presence of stochastic shocks (EIO and Dynamic Stochastic General Equilibrium models)[13]. These models are capable of evaluating the consequences of carefully designed interventions in the macroeconomic system through changes in relative prices or technological coefficients ("what happens if?").

Evaluation of top-down models. A summary and stylized cross-model comparison of the discussed strengths and weaknesses of top-down models is given in Table 2. These top-down models are all able to explore the consequences and indirect effects of "localized" shocks (e.g. the introduction of a policy or technology at the sectoral level) to final demand (domestic/foreign), other sectors and at the aggregate level (e.g. GDP), differentiated by region. However, in their default set-up all of them are poor with respect to sector-specific stock-flow interactions as well as financial market dynamics (i.e. they are models of the "real" economy). Additionally, they are comparably coarse with respect to technological detail, a trade-off that allows for depicting the whole market economy within one modeling framework. This explains the recent surge in linking bottom-up models to top-down models in order to account for the strengths of both modeling types, which is the focus of the next section.

[12] Note that integrated assessment models like DICE (Nordhaus 2017) bridge this gap explicitly by linking climate models with economy models. However, both representations remain highly stylized due to computational constraints. The economic part, for instance, refrains from *multi-sector* multi-region representations, which is why we exclude IAMs in this review.

[13] This follows from the definition that macro phenomena involve strong emergence if they cannot be deduced from micro phenomena. Weak emergence follows from unexpected but deducible micro phenomena (Chalmers, 2008).

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Table 2: Stylized comparison of three macroeconomic modeling approaches.

Stylized model comparison	**Computable General Equilibrium (CGE)**	**Input-Output Models (IO)**	**Econometric Input-Output Models (EIO)**
Which question(s) does it answer?	Consequences and indirect effects of "localized" shocks (e.g. the introduction of a policy or technology at the sectoral level) to final demand (domestic/foreign), to other sectors and at the aggregate level (e.g. GDP), differentiated by region (drawn upon e.g. in macroeconomic cost-benefit analysis)		
How?	Relative price mechanism based on optimization (profit/utility maximization)	Inter-sectoral economic flows based on fixed input/output coefficients	Statistically estimated functional relationships
Main data input	Single year social accounting matrix	Single year input-output table	Panel of time-series data, input-output tables
Paradigm	Walrasian, Neo-classic	Leontief	(Post-)Keynesian
Angle	Long-run equilibrium	Short-run rigidities	Short-to-long run
Constrained by	Supply-side (optimal full utilization of production capacity)	Demand-side (production factors available in fully elastic supply)	Demand-side (non-optimal idle available production capacities)
Price responsiveness to changes in costs	Strong	None	Weak
Strengths/ Weaknesses	(+) Capturing indirect effects between sectors/agents/regions (+) Endogenous structural/technological adjustment possibilities through estimated elasticities of substitution (-) Absent sector-specific stock-flow interactions (-) Low technological detail (+/-) Money neutrality	(+) Capturing indirect effects between sectors/agents/regions (-) Absent sector-specific stock-flow interactions (-) Low technological detail (+/-) No endogenous structural adjustment possibilities (+/-) Money neutrality	(+) Capturing indirect effects between sectors/agents/regions (-) Absent sector-specific stock-flow interactions (-) Low technological detail (-) Estimated relationships deal poorly with historical structural breaks (+/-) Implicit: "Money is *not* neutral"
Examples	WEGDYN (Mayer et al., 2019)	Eora (MRIO) (Lenzen et al., 2013)	E3ME (Barker et al, 2012)

3.4. Exploiting synergies by linking macroeconomic and sector-specific models

Why linking models? We have discussed the various strengths and weaknesses of bottom-up and top-down models in sections 3.2 and 3.3. Linking these models is of special interest because, first, this can improve the representation of technologies (e.g. power, heat and cogeneration) and sector-specific stock-flow relations (i.e. capacities differentiating age, efficiency, etc.) in comprehensive macroeconomic assessments and, second, this allows to provide aggregate demand feedbacks derived by the top-down model back to the bottom-up model. To implement the interplay between models of different scope and complexity, two types of linkage are commonly used: hard-linking and soft-linking.

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Hard-linking

Hard-linking of models implies that two or more problems are implemented in a single model. This linking is used in order to capture a bidirectional interaction. For the focus of this review, this approach implies that heat and electricity supply are optimized or simulated within a single model. Nevertheless, hard-linkage is not always practical or desired because it leads to significant increases in models size and complexity. What dictates the choice of this approach is, thus, the tradeoff between the representativeness of the results and the model's computability (i.e. size and complexity). In terms of accuracy, this is the preferred implementation when endogenous variables of the different models affect each other, because it ensures consistent results.

Hard-linking power and heat and models and macroeconomic models. To include the heating sector into power system models, the large majority of the analyzed literature use hard-linkage, i.e. electricity and heat sector are represented in one more comprehensive model. Some examples for hard-linking between electricity and heat sectors include Balmorel (Wiese et al., 2018), Energy Plan (Connolly et al., 2016) and MICOES-Europe (Böttger et al., 2015). There are many examples of bottom-up energy models hard-linked to top-down macroeconomic models (Bosetti et al., 2006; Strachan and Kanan, 2008). These studies, however, use simplified representations of either the bottom-up or the top-down model. To our knowledge, the only study that retains hard-linkage – whilst covering multiple economic sectors and combining detailed and extensive technology data with disaggregated economic structure – is the one presented by Helgesen et al. (2018).

Soft-linking

Soft-linking leaves models separate but uses output data from one model as input data for the other model. If the actual interaction is unidirectional, it is possible to solve the independent model first and the dependent model second without a loss of accuracy i.e. a deviation from the global solution. The solution deviates from the global solution when a bidirectional interaction is simplified to a unidirectional one. The main advantage of soft-linking is its simplicity (it is easier to compute and often results are easier to interpret).

Soft-linking power and heat models and macroeconomic models. In the context of heat-electricity interaction, soft-linkage implies that separate models[14] are employed to model the electricity system and the heating system. This approach is used under the assumption that the interaction between the markets is such that simply using the results of one model as an input for the other model does not result in a loss of optimality i.e. in a significant deviation from a global solution. If both models mutually influence each other, the process of data exchange may iteratively be repeated. Ideally, such iteration converges towards a near-optimal solution. Many of the reviewed papers use heat demand as an (exogenous) input parameter. Because these heat demand series are calculated using other models, this can be considered as soft-linkage. Only a minority of papers hard-link electricity supply and heat

[14] Separate models can be run independently but do not necessarily need to be in different code bases.

supply models (e.g. Bauermann et al., 2014; Deane et al., 2012). Soft-linking bottom-up models of energy with top-down models of the whole economy has a long history (see Anderson et al., 2019, and the references found therein). Recent trends are soft-linking bottom-up and top-down models in a full-form full-link approach (e.g. Dai et al., 2016; Fortes et al., 2014).

4. Summary of key findings

Various socio-economic and techno-environmental trends are present in the energy transition and make evaluating trade-offs a necessity. It is yet unclear, whether (and how) the rate and direction of such trends can be influenced in order to mitigate conflicts and exploit synergies. This lack of clarity is due to the complexity of real-world (energy) systems and the related uncertainty. Models deal with complexity and uncertainty in different ways. Recently, pathway approaches ("what happens if?") gained traction. They address energy related research questions from different angles, which helps to avoid illusions of first-best worlds as often communicated "from the ivory tower" by researchers. These pathway approaches have also highlighted that inter- and transdisciplinary embedding is valuable and highly needed, not only to increase policy relevance but also for the research community itself.

This review builds on the key observation that sector interaction is crucial in energy transition and thus multi-sectoral approaches – in the analysis and modelling – are crucial to understand core issues of the energy transition. Models have different scopes; they particularly differ with respect to their representation of interdependencies between producing sectors and consumers. We review both classes of approaches, bottom-up and top-down. Bottom-up models of our interest are power sector models, and top-down models are macroeconomic models with endogenous energy demand. Given its increasing practical relevance, we put a specific emphasis on existing analyses of power-heat linkages. This link is expected to involve large potentials in terms of energy supply and greater flexibility. We also discuss this linkage under the two angles from which it can be analyzed – from a bottom-up and from a top-down point of view (section 3.1.1). We provide a review of studies dealing with power-heat linkages from both angles (sections 3.2-3.3).

We identified three dimensions that play a major role in making the bottom-up literature heterogenic. The fist dimension categorizes models according to whether dispatch and investment decisions are captured endogenously, the second dimensions reflects the fundamental difference between central and decentral supply and the third dimension captures sets of features which are implemented depending on the focus of the publication. A further obstacle to a detailed representation of the heat market is the issue of data availability. Data availability is low and scattered when compared to the electricity market models. Data availability can limit the possibility of heating models to represent an issue depending on the case study – unless a reasonable way to estimate missing data exists.

The interaction across individual sectors can be embedded in a macroeconomic framework. Both sectors – power and heating – are parts of long economic value chains. Thus, economy-wide effects and repercussions have to be acknowledged in order to avoid or manage

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detrimental socio-economic consequences. Hence, a distinct feature of top-down models (compared to bottom-up models) is to endogenize (energy) demand. A further strength of macroeconomic models is the evaluation of market-based system-wide indicators (e.g. prices, unemployment, consumption, GDP), but they can also take into account non-market aspects of well-being (e.g. health). We review a sample of macroeconomic models in section 3.3, which investigate issues of power and heating and find that heating, and in particular the link of power and heat, is a comparably underrepresented object of analysis.

For assessing the long-term low carbon transformation, Schinko et al. (2017) have highlighted mutual challenges to all market and economic impact models (bottom-up and top-down). Given the size of the research agenda, a systematic application and integration of different models and methods is a reasonable and fruitful approach (section 3.4). In the bottom-up literature, some standard practices have emerged in the modeling of the electricity market that benefits from a longer and richer literature. This might be one of the reasons why the integrated representation of the electricity and heat market is frequently achieved by linking a "main" electricity market model with an "add-on" heating market model. A similar approach can be found in the literature on linking individual energy sector models with top-down macroeconomic models. Hence, the design of the integrated model depends on how these models are assumed to interact. Soft-linking is an option which has benefits in terms of computational tractability (and modularity). On the other hand, using hard-linking can be necessary when the model intends to capture simultaneous bidirectional mechanisms.

Both angles – bottom-up and top-down – offer valuable insight reflecting on and guiding the design of future energy markets. However, current models of both angles are subject to various deficiencies, especially in their stand-alone applications. While bottom-up models incorporate many details of individual markets at the expense of comprehensiveness, the opposite applies for top-down models. This is particularly salient in light of the role that sector coupling (and in particular the coupling of the electricity and the heat sector) is expected to have. The number of bottom-up models investigating power-heat relations is increasing reflecting a new strand of literature. On the other hand, this link is rather underexplored in top-down assessments, which quantify its economic implications. Based on this observation, improving not only these approaches individually but, in particular, developing a (soft-)link between bottom-up and top-down models seems to be promising in order to exploit and combine the strengths of individual methods.

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6. Appendix A – Heat applications and linking technologies

He(a)terogeneity. Heat is not a homogenous good. The value of heat differs by temperature (high temperature heat is more valuable due to the higher exergy content), by time (like electricity, heat tends to be more valuable when the heat demand is high) and by the location of the demand (transport of heat is subject to significant losses and economic viability therefore declines at increasing distance). This heterogeneity must be considered when modeling the interaction of heat and electricity.

Applications. A criterion to distinguish heat is its application. We distinguish between space heating, hot water, and industrial heating. These distinct applications have their characteristic temporal demand patterns and require heat at certain temperature levels.[15] Both temporal variability and temperatures are relevant parameters for possible heat-electricity technologies and their modeling, as we discuss in the following.

Heat applications

Space heating. Depending on the climate, space heating is the largest heat application in most European countries. This application features an intrinsic seasonal variability, mostly driven by the ambient temperature: the lower the ambient temperature, the higher the heat demand. This connection is time-lagged by the thermal inertia of the building mass. This seasonal variability is superposed by diurnal variability resulting from the behavior of the space occupants. For example, many households lower the indoor temperature at night, which implies a lower heat demand at night and a heating peak in the morning, when heating devices are switched on. Other influencing factors are solar radiation, and wind speed which accelerates thermal dissipation. The temperature level at which space heat is supplied also depends on the ambient temperature (the lower the ambient temperature, the higher the temperature that the heat must be supplied at) and on the heat distribution system in the building (it is generally higher for radiators than for panel heating, such as floor heating).

Modeling space heating. Space heating is not centrally monitored and hence there are no official heat demand time series available (see section 3.2.4 on data availability). The approaches of modeling heat demand time series can be distinguished into models of buildings and statistical approaches. Building models use thermodynamic equations to infer the heat demand from outdoor temperatures. The main physical building parameters in these models are heat capacity (how much energy can be stored in the building mass) and heat transfer coefficients (how good is the building insulation). As a result, building models are well suited to capture changes in the building stock, e.g., better insulation with new and retrofitted buildings. Exemplary heat-electricity models using this approach are Hedegaard et al. (2013), Arteconi et al. (2016), and Cooper et al. (2016). In contrast, statistical approaches estimate the connection between heat demand and ambient temperatures from empirical observations. These estimations can be represented in the form of standard load profiles, as

[15] A heat source at high temperature can be used to supply applications that consume heat at a lower temperature. The opposite is not possible without spending additional energy.

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for instance used by Fehrenbach et al. (2014) and Ruhnau et al. (2019a). Statistical approaches often consider calendar effects (weekly and diurnal patterns), which implicitly captures user behavior.

Hot water. The demand for hot water mainly follows a diurnal pattern, driven by the user behavior (other calendar effects may play a role). Modelling thus mainly relies on statistical approaches. Some models additionally capture the effect of the seasonally varying cold-water temperature, because this temperature defines how much heat is needed to reach the required hot water temperature (Fischer et al., 2016). The hot water temperature must exceed 60 °C to prevent legionella bacteria.

Industrial heat. The demand for industrial heat is very heterogenic. The temporal demand profiles depend on individual work and shift schedules; diurnal and weekly pattern can be expected rather than seasonal effects. The required temperature levels are often much higher than for space and water heating, but this depends very much on the industrial process. On the other hand, there is a huge and diverse potential for waste heat recovery (Miró et al., 2016). Because of this heterogeneity, a general modeling of industrial heat is seldomly applied. We therefore focus on reviewing approaches for space heating and hot water in the following.

Power-to-heat

Intro. One option to connect the power and heat sectors are power-to-heat technologies. By power-to-heat, we refer to components that consume power and produce heat. These include electric heaters and electric heat pumps.

Electric boilers. The simplest power-to-heat technology are electric heaters. Within electric heaters, resistance heaters and electrode heaters can be distinguished. With both technologies, the conversion efficiency is close to unity and operation can be very flexible without negative side-effects. The modeling of electric heaters is straight-forward and does not vary across studies. The heat output is proportional to the power input, with the efficiency η being assumed constant:

$$heat\ output_t = \eta \cdot power\ input_t$$

Electric heat pumps. Electric heat pumps also consume power as an input, but they additionally use a heat source. Different heat pump technologies can be distinguished by the heat source: air, ground, and groundwater. The ratio between the supplied heat and the used electricity is given by the coefficient of performance (COP). The corresponding model equation is similar to that of electric heaters:

$$heat\ output_t = COP_t \cdot power\ input_t$$

Comparison. A difference between heat pumps and electric heaters is that the COP is not constant: it depends on the temperatures of heat sources and heat sinks. The lower the difference between these temperatures, the higher the COP. For air and ground source heat pumps, the source temperature varies significantly over time. For space heating, also the sink temperature varies given that the required temperature level depends on the ambient temperature. Thus, the COP of these heat pumps varies. Further influencing factors on the COP are losses due to part-load and cycling. The studies that cover this volatility can be distinguished into two groups. The first group (e.g. Arteconi et al., 2016) builds on the Cournot law, which describes an upper bound to the efficiency of heat pumps (and thermodynamic processes in general). This approach is modified with two empirically estimated parameters A and B, as described by Bettgenhäuser et al. (2013):

$$COP_t = \frac{A \cdot T_{sink,t}}{T_{sink,t} - T_{source,t} + B}$$

Other studies use linear or quadratic regression models to estimate the COP from the temperature difference between heat source and sink. These models are fitted on manufacturer data or field measurements (e.g. Chen et al., 2014; Ruhnau et al., 2019a):

$$COP_t = a_0 + a_1 \cdot \Delta T_t + a_2 \cdot \Delta T_t^2$$

Combined heat and power

Definition and technologies. Another option to couple power and heat sector is the cogeneration of heat and power. This process requires a non-electricity source as input, for example fossil or biofuels or geothermal sources. We distinguish three technologies with different degrees of flexibility:

(1) Combustion engines and gas turbines with heat recovery: Heat is recovered from the excess air. The heat output is therefore proportional to the power output, hence the required heat defines a lower bound for the power output; the power output can exceed this lower bound as needed.

(2) Extraction-condensing steam turbines: Just as with (1), the potential heat output is proportional to the power output, but when heat is extracted, this comes at a power loss.

(3) Backpressure steam turbines: The heat output is necessary for the power production process; heat and power are tightly coupled to each other.

Modeling. The connection between heat and power output can be described by the power-to-heat ratio σ:

$$\sigma_t = \frac{power\ output_t}{heat\ output_t}$$

For heat recovery and extraction-condensing steam turbines, the heat output can always be decreased, so $\sigma_t \geq \sigma$, while the power-to-heat ratio is fixed for backpressure turbines, $\sigma_t = \sigma$. For extraction-condensing turbines, the power loss coefficient β can be expressed as follows:

$$power\ output_t \leq max\ power\ output - \beta \cdot heat\ output_t$$

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Thermal storage

Relaxing the heat constraint. Power-to-heat and CHP plants constrain either power consumption or power generation to the heat demand. Thermal storage can relax this constraint, and therefore lead to a more electricity-oriented operation of these linking technologies. Their lower CAPEX compared to electricity storage make heat storages in some cases economic efficient. Thermal storages are typically water tanks, but many other technologies also exist. In practice, these storages may be located next to the end-consumer of heat (decentral) or near the generation, e.g. a CHP plant (central).

Storage losses. Generally, storage losses increase with higher storage temperatures. The use case determines which temperatures are required: due to hygienic standards, domestic hot water storages require for example higher temperatures than floor heating systems (Bloess, 2018). In models, two common approaches are used to account for storage losses: dynamic and stationary losses. Dynamic losses occur when charging or discharging the storage. By contrast, stationary losses describe the losses of a charged storage over time. Sometimes, these stationary losses are neglected for large-scale storages, e.g. for district heating (e.g. Nielsen et al., 2016; Salpakari et al., 2016).

Passive storage. In addition to the previously described active storage, one can consider the thermal inertia of buildings as a passive storage; heat can be stored in the building structure (Hedegaard et al., 2012; Hedegaard and Balyk, 2013). Defining lower and upper temperature levels for heating is a means to consider these passive storages in models. This formulation requires a precise modelling of the houses and heat appliances and is therefore not included in most power system models. Passive storages are not directly represented but indirectly assumed by a more flexible heat demand.

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7. Appendix B – Literature overview for power-heat linking

Table A.1: Overview of the reviewed literature. Most models include centralized and decentralized heat supply appliances (grew columns) and optimize their dispatch (y in dispatch column); only few models also optimize investment in these technologies (y in investment column).

	Centralized heat supply			**Decentralized heat supply**		
	Included	**Dispatch**	**Investment**	**Included**	**Dispatch**	**Investment**
Arteconi et al. (2016)				y	y	
Bach et al. (2016)	y	y				
Barton et al. (2013)				y		
Bauermann et al. (2014)	y	y	y	y	y	y
Blarke (2012)	y	y				
Connolly et al. (2016)	y	y		y	y	
Cooper (2016)				y		
Dodds (2014)	y			y	y	y
Ehrlich et al. (2015)				y	y	
Fehrenbach et al. (2014)	y			y	y	y
Georges et al. (2017)				y	y	
Hedegaard and Balyk (2013)	y	y	y	y	y	y
Hedegaard and Münster (2013)	y	y	y	y	y	y
Hedegaard et al. (2012)	y	y		y	y	
Hughes (2010)				y	y	
Heinen et al. (2016)				y	y	y
Henning and Palzer (2014)	y	y	y	y	y	y
Kirkerud et al. (2014b)	y	y		y	y	
Kiviluoma and Meibom (2010)	y	y	y			
Liu et al. (2016)	y	y	y			
Lund et al. (2010)	y	y	y	y	y	
Mathiesen and Lund (2009)	y	y		y	y	
Merkel et al. (2017)				y	y	y
Münster et al. (2012)	y	y	y	y		y
Nielsen et al. (2016)	y	y				
Østergaard et al. (2010)	y	y		y	y	
Østergaard and Andersen (2016)	y	y		y	y	
Østergaard and Lund (2011)	y	y		y	y	
Papaefthymiou et al. (2012)				y	y	
Patteeuw et al. (2015)				y	y	
Patteeuw and Helsen (2016)				y	y	y

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Table A.1(ctd): Overview of the reviewed literature. Most models include centralized and decentralized heat supply appliances (grew columns) and optimize their dispatch (y in dispatch column); only few models also optimize investment in these technologies (y in investment column).

Schaber et al. (2013)	y	y	y	y	y	y
Teng et al. (2016)				y	y	
Waite and Modi (2014)				y		
Wiese et al. (2018)	y	y	y			

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8. Appendix C – Literature overview: macroeconomic studies on power and/or heat

Table A. 2: Web-of-Science based query on macroeconomics of power and heat excluding (81-52=)29 papers based on their abstracts (as of 30.01.2020).

			Topic			Method						Approach		
No.	**Author(s)**	**Year**	**Energy**	**Electricity or Power**	**Heat**	**CGE**	**Econometric**	**IAM**	**Input-output**	**System dynamic**	**Agent-based**	**Bottom-up**	**Top-down**	**Hybrid**
1	Gupta et al.	2019	Y	Y								Y	Y	Y
2	Sievers et al.	2019	Y	Y	Y					Y				
3	Paim et al.	2019	Y	Y				Y						
4	Komendantova et al.	2019	Y	Y		Y								
5	Kat et al.	2018	Y	Y		Y								
6	Sers et al.	2018	Y							Y				
7	Kiuila	2018	Y	Y		Y						Y	Y	Y
8	Pereira and Pereira	2018		Y		Y								
9	Malaczewski	2018	Y	Y		Y								
10	Lee et al.	2018	Y	Y			Y							
11	Ponta et al.	2018	Y	Y							Y			
12	Shafiei et al.	2018	Y	Y						Y		Y		
13	Hasudungan and Sabaruddin	2018	Y	Y		Y								Y
14	Graziano et al.	2017		Y		Y								
15	Papageorgiou et al.	2017	Y				Y							
16	Lu et al.	2017	Y	Y		Y								
17	Fragkos et al.	2017	Y	Y		Y								
18	Su et al.	2017	Y	Y					Y					

SENTINEL

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Table A. 2(ctd): Web-of-Science based query on macroeconomics of power and heat excluding (81-52=)29 papers based on their abstracts (as of 30.01.2020).

19	Blazquez et al.	2017	Y	Y		Y						
20	Argentiero et al.	2017	Y			Y						
21	Bretschger and Zhang	2017	Y			Y						
22	Duscha et al.	2016	Y	Y			Y	Y				
23	Wang et al.	2015	Y	Y		Y						
24	Akkemik and Li	2015	Y			Y						
25	Vennemo et al.	2014	Y	Y		Y						
26	Wei and Rose	2014		Y				Y				
27	Wiskich	2014	Y	Y		Y				Y	Y	
28	Pollitt et al.	2014	Y	Y			Y					
29	Bartocci and Pisani	2013		Y		Y						
30	Di Cosmo and Hyland	2013	Y	Y			Y					
31	Asafu-Adjaye and Mahadevan	2013	Y	Y		Y						
32	Proenca and St Aubyn	2013	Y	Y		Y				Y	Y	Y
33	Bosello et al.	2012	Y	Y		Y						
34	Lehr et al.	2012	Y	Y	Y		Y	Y				
35	de Arce et al.	2012	Y	Y				Y				
36	Lin and Jiang	2011	Y	Y		Y						
37	Trink et al.	2010	Y		Y	Y						
38	Bartleet and Gounder	2010	Y	Y			Y					
39	Howells et al.	2010	Y	Y					Y			
40	Dagoumas and Barker	2010	Y	Y			Y			Y	Y	Y
41	Mathy and Guivarch	2010	Y	Y		Y						

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Table A. 2(ctd): Web-of-Science based query on macroeconomics of power and heat excluding (81-52=)29 papers based on their abstracts (as of 30.01.2020).

42	Pereira and Pereira	2010	Y	Y			Y				
43	Labandeira et al.	2009		Y		Y					
44	Wing	2008	Y	Y		Y			Y	Y	Y
45	Klaassen and Riahi	2007	Y	Y		Y			Y	Y	
46	Grepperud and Rasmussen	2004	Y	Y		Y					
47	Steininger and Voraberger	2003	Y	Y	Y	Y					
48	Welsch and Ochsen	2001	Y	Y		Y					
49	Cooper et al.	1999	Y	Y		Y					
50	Jacobsen	1998	Y	Y		Y			Y	Y	
51	Welsch	1998	Y	Y		Y					
52	Barker et al.	1993	Y	Y			Y	Y			