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What Will Make Energy Systems Sustainable?

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566/2018

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AUSTRIAN INSTITUTE OF ECONOMIC RESEARCH

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WIFO Working Papers, No. 566

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2018/137/W/0

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WIFO Working Paper

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Abstract

One of the lessons learned from the German effort under the heading of Energiewende is the insight that simply shifting to renewables and recommending improving energy efficiency is not sufficient to lower greenhouse gas emissions. Combined with the expected radical change of technologies this requires a more profound understanding of our energy systems. Therefore, in contrast to most conventional approaches we propose a deepened structural analysis that covers the full energy value chain from the required functionalities for mechanical, thermal and specific electric energy services via application and transformation technologies up to primary energy. This deepened structural approach opens and substantially enhances our understanding of policy designs that are compatible with the Paris Agreement and Sustainable Development Goals. We discover the essential role of four energy grids, namely for electricity, heat, gas, and information as the key for integrating all components of a newly structured energy system. Consequently, we conclude that policy strategies focusing on individual components of an energy system as simply shifting to renewables may from a comprehensive perspective on sustainability in the worst case even turn out as counterproductive.

JEL codes: Q01, Q40, Q55

Keywords:

Sustainable energy systems, Energy value chain, Energy grids

Acknowledgements

Funding for previous projects by the Austrian Climate and Energy Fund and Austrian Federal Governement is kindly acknowledged.

1 Introduction

The expected radical changes of energy systems

Energy systems face far reaching changes substantiated on the one hand by the Paris Agreement (UNFCCC 2015) and on the other by deep technological change (MIT Energy Initiative 2016; Heinonen, Karjalainen, and Ruotsalainen 2016; Breit, Rao, and Gürtler 2018). Both challenges are closely interlinked if one focuses on targeted technological breakthroughs, as building structures that collect more energy than they consume, mobility that is partially fulfilled by advanced information technologies, e.g. based on holography, or grid structures for electricity, heat and gas that are coupled and become bi-directional.

The uncertain impact on sustainability

Ultimately, we expect that energy systems meet the qualities of sustainability as any other actions related to our life styles and economies. What this really means for the transformation of energy systems is less obvious. This is one of the lessons learned from the German effort under the heading of Energiewende (Agora Energiewende 2017) as the focus on a shift to renewable turned out to be not sufficient, although this deliberate policy effort has triggered the take-off of wind power and photovoltaics on a global scale. Despite this effort in renewables, which account now for about one third of electricity production, greenhouse gas emissions in Germany have not significantly decreased (Clean Energy Wire 2018; Agora Energiewende 2018).

Caveats and restrictions for the transformations

Since energy systems are intimately woven into any other resource use for personal or business purposes, the same caveats and restrictions apply, as observing the planetary boundaries (Steffen et al. 2015) or the Sustainable Development Goals (UN 2015). Given this perspective, we provide operational guidelines for putting energy systems on a sustainable trajectory that encompass much more than the conventional recommendations of shifting to renewables and improving energy efficiency.

We put forward the proposition that this requires a deepened understanding of the internal structure of energy systems, ranging from the still not well-known functionalities for thermal, mechanical and specific electric services via the full energy value chain up to primary energy. This opens a broader perspective on targeted transitions of our energy systems that emphasizes the role of grids and technological innovations on each layer of the energy value chain in addition to the substitution of fossil energy sources by renewables. This approach enables handling the implication of radical technological change and allows the discovery of synergies from a much better integration of all components of the energy system. As a key result we obtain insights about the role of newly designed energy grids for electricity, heating and cooling, gas and information technologies as a driver for sustainability.

Why we need a broader perspective for targeted transitions

We put forward the proposition that this requires a deepened understanding of the internal structure of energy systems, ranging from the still not well-known functionalities for thermal, mechanical and specific electric services via the full energy value chain up to primary energy. This opens a broader perspective on targeted transitions of our energy systems that emphasizes the role of grids and technological innovations on each layer of the energy value chain in addition to the substitution of fossil energy sources by renewables. This approach enables handling the implication of radical technological

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2 A framework for integrated energy system analysis

For analyzing radical transformations of energy systems along sustainable trajectories, a deepened structural analysis provides guidance for transition strategies. This effort is closely tied to the need for advancements in analytical approaches since current modelling approaches face limitations when it comes to their ability to deal with the long-term evolution of technologies and economic structures as addressed e.g. by (Pindyck 2017), (Rosen and Guenther 2015) and (Stern 2016).

2.1 The limits of conventional approaches to analyzing energy systems

Searching for methodological approaches that are suitable for long-term transformation processes

There is emerging evidence that existing methodological approaches to analyzing energy systems have fundamental deficiencies that limit their potential to discover the subtleties of long-term transformation processes. Mainstream modelling designs as econometric, computable general equilibrium, New Keynesian or complex Integrated Assessment models (IAMs) in general are characterized by an almost complete absence of details of the complete energy value chain (Schinko et al. 2017), in particular they lack to model the central role of functionalities - namely the thermal, mechanical and specific electric services - that are provided by the interaction of energy flows and corresponding capital stocks. Focusing on the entire energy value chain, starting from these functionalities up to primary energy, provides a perspective on energy application and transformation that allows integrating relevant technological innovations on each layer of the energy chain just as the substitution of fossil energy sources by renewables.

A deepened view of the structure of energy systems

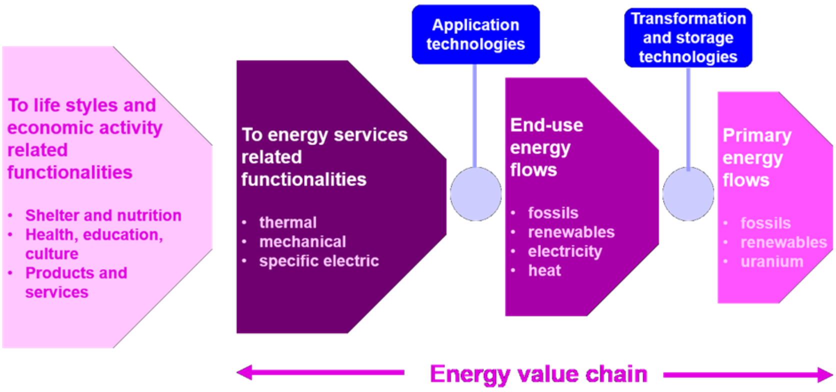
With such a deepened view of the energy system we put forward the following proposition: Since many suggestions for a sustainable transformation of current energy systems have turned out too simplistic by focusing mainly on the substitution of fossils by renewables, we propose that in the context of energy sustainability this requires lowering total energy flows without compromising the required functionalities instead of only relying increasingly on renewables. Consequently, we emphasize the need for a deepened understanding of the complete structure of energy systems which also reveals the essential role of four grids - electricity, heating and cooling, gas, and information - that need to interact.

2.2 Revealing the full energy value-chain

Focus on functionalities and the full energy value chain

Our deepened structural modeling approach to identifying sustainable energy systems builds on two key features: We focus on functionalities for thermal, mechanical and specific electric services as the ultimate purpose of any energy system; then starting from these functionalities we analyze the full energy value chain via application, transformation and storage technologies until we arrive at primary energy needs. This deepened structural view of energy systems as depicted in Figure 1 reveals the essential role of integrating grids that will be operated in bi-directional modes and deal with interactions between them. The grid structure in an advanced energy system encompasses more than a separate perspective on electricity, heat or gas grids. In a highly efficient energy system the new role of grids for gas and the integrating role of information grids has to be taken into account and implies above all that electricity needs to be coupled with heat.

Figure 1. Revealing the entire energy value-chain



Source: Adapted from (Köppl et al. 2014) and (Schleicher et al. 2018)

An alternative way for long term analyses of decarbonized structures

This conceptual framework for energy system analysis is based on previous analytical work that applies this deepened structural modeling as methodological approach (Köppl et al. 2014; Schleicher et al. 2018; Köppl et al. 2016; Köppl and Schleicher 2014). It recommends for an alternative way for long term analyses of decarbonized structures, as the current understanding of the energy, emission and economic system, that mainly focuses on the availability of (energy) resources, prices and the close correlation between GDP growth, resource use and emissions, is increasingly questioned (cf. Schleicher et al. 2016), as is GDP as measure for wellbeing (e.g. Stiglitz, Sen, and Fitoussi 2009). In the context of long-run transformation research (e.g. WBGU 2011; Goepel 2016) interest is growing on how to define and measure human well-being meaningfully and in a way that respects planetary boundaries (Raskin, Electris, and Rosen 2010; Raworth 2017; Helliwell, Layard, and Sachs 2018). This is of utmost relevance for the energy system where we already observe far reaching transitional processes. Examples are the emerging integrated micro-grids for universities, business and residential areas (IEEE Spectrum 2017; Bollinger and Evins 2017).

Beyond mainstream energy and emission analysis

Mainstream energy and emission analysis (cf. Weyant and Kriegler 2014) mainly focus on energy flows and the generated greenhouse gas emissions whereas our deepened structural modelling approach strongly emphasizes the crucial role of functionalities and their dependence on the stocks of technologies used together with energy flows along the full energy value chain up to primary energy.

A promising method for understanding and evaluating the expected radical transformations of energy systems

With this perspective we depart from conventional analysis that typically chooses the availability of primary energy as starting point. Emphasizing functionalities and the entire energy value chain in contrast allows to stress and analyze the role of different application and transformation technologies in generating energy services, e.g. for the functionalities in buildings and for mobility as well as the transformation and storage for electricity and heat. This goes far beyond concepts that mostly deal with incremental technological progress driven by changes in relative prices as in many mainstream analytical approaches. Such an integrated perspective of the whole energy value chain demonstrates that the different layers are interlinked and therefore should be addressed jointly. It starts from the demand side, the desired functionalities, and connects it to the production side via investment activities and energy flows during the operating phase over the whole lifetime of the capital stocks. We argue that this deepened structural approach is a promising method for understanding and evaluating the expected radical transformations of energy systems.

2.3 Underlining the interaction between energy flows and the related capital stocks

The required functionalities depend on stocks and flows

Essential for a better understanding of these challenging transition processes is the focus on functionalities, the ultimately expected energy services, which result from the interaction between stocks and flows, to serve (basic) human needs such as shelter, nutrition, health, education and culture. The thermal services in buildings e.g. depend on the quality of the building stock and the related energy flows. Mobility is from a functionality perspective the access to persons, goods and locations, and depends on different spatial allocations of economic activities, locations for residence, transport technologies, transport modes and increasingly communication technologies as tele-conferencing and tele-working.

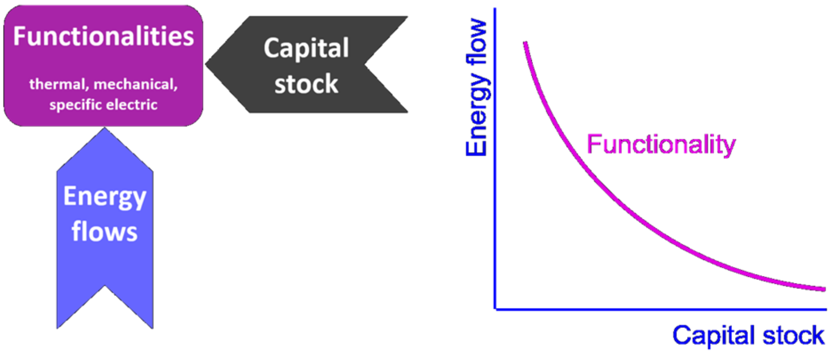
An integrated view shifts from economies of scale to economies of scope

This aspect of the deepened structural modeling approach highlights the interaction between capital stocks (including technologies they represent) and flows for providing a specific functionality. The diffusion and use of technologies that are often characterized by disruptive change impact the energy and emission system on the one hand and shape economic structures on the other. Disruptive change, from an analytical point of view, can arise from a shift in the focus from economies of scale, e.g. cost reductions with increasing scales of production, to also consider economies of scope, e.g. by using cogeneration technologies for electricity and heat. Such changes strongly concern and affect investment decisions that result from an integrated view of the energy system or new options for decentralized structures but also comprise changes in behavior, lifestyles, social practices, and business models.

The essential stock-flow relationships

The focus on functionalities and the relevance of the interaction of stocks and flows is illustrated in Figure 2. The curve illustrates a specific constant functionality that results from resource flows and capital stocks. The constant level of a specific functionality is provided by a combination of the capital stock and resource flows. Along the curve to the right are those combinations where a larger capital stock, e.g. more public transport or a capital stock of higher thermal quality, e.g. buildings with an improved thermal quality, requires much less resource flows for the provision of the required functionality.

Figure 2. Relevance of stocks and flows for providing functionalities



Source: Adapted from (Köppl et al. 2014) and (Schleicher et al. 2018)

3 The role of grids for sustainability of energy systems

What was overlooked so far in most long-term visions of targeted transitions of energy systems are the interdependencies between the different layers along the energy value chain that need to be considered when providing the thermal, mechanical and specific energy services summarized under the heading of functionalities. Key elements for enabling these interactions are the grids for electricity, heating and cooling, and gas. These grids, however, will also be subject to fundamental transformations that are revealed by adding an integrating information grid.

3.1 General guidelines for sustainable transition trajectories

This holistic view of an energy system offers insights about the internal structure and options for change and improvements. Identifying these options requires a much subtler argumentation than substituting fossils by renewables and improving energy efficiency. At least three qualities of an energy system need to be considered for a transition to a low-energy and low-carbon structure, which are necessary for sustainability requirements.

The efficiency criteria of thermodynamics and the phase-out of fossils

Firstly, we aim for a lower amount of energy for providing the expected functionalities or energy services, e.g. by improving the thermal structure of buildings. This criterion is based on the First Law of Thermodynamics, which is known under the term mass efficiency. Secondly, it is the quality and not only the quantity of energy that is applied to provide a functionality, which calls for considering the ability of an energy source to provide mechanical work. This criterion is based on the Second Law of Thermodynamics, which is known under the term exergy efficiency. Thirdly, for the decarbonization of the energy system a reduction of the amount of fossils in the mix of primary energy is needed. Together these three criteria provide operational guidelines for the transformation of energy systems as illustrated by the following examples.

Implications for buildings

Buildings typically consume currently a third of final energy, mainly for low-temperature energy services. According to our criteria for the design of energy systems that meet the long-term transition targets, it follows that a high mass efficiency by improving the thermal structures is desirable. In addition, a waste of exergy efficiency should be avoided. This would be the case if low- temperature heat is provided by energy sources with a high but unused ability to provide mechanical work, as electricity, oil products or gas.

Implications for mobility

Transport typically uses another third of final energy, mainly fossil fuels and some electricity for rail transport and e-mobility. Besides strategies that reduce the need for transport - as a localization of production and the application of communication technologies - a significant increase in the number of electrical drive systems is expected over the next years. The evolution of this technology, however, will strongly depend on battery technologies, the infrastructure for battery charging, but also the strategies of the automotive industry.

Implications for industry and manufacturing

The last share of final energy is needed for industry and manufacturing. A main determinant is the industry structure of the economy, in particular the share of energy-intensive industries of a country. Sectoral roadmaps for low-energy and low-emission structures in industry are emerging, e.g. for cement, steel, paper and pulp industry (European Commission 2011).

The benefits of cogeneration of electricity and heat

Final energy results from the transformations of primary energy. If we scrutinize these processes with respect to mass and exergy efficiency criteria, potentials for the desired transition of energy systems emerge. Special attention deserve thermal processes, which typically use stand-alone technologies, such as providing just heat or just electricity. According to the Second Law of thermodynamics it is highly recommended to switch to cogeneration technologies which exploit besides thermal also mechanical services. Thus, from one input, e.g. gas, two outputs are generated, namely heat and electricity, which in turn can be used for heat pumps that collect free ambient heat. Such a setup substantially increases the efficiency of primary energy.

3.2 Discovering synergies via integrated grid structures

A number of implications follow from this comprehensive view on energy systems for the future role of grids in view of the proposed criteria for evaluating them.

Four bi-directional grids

Given the decisive role of functionalities, four grids need to be considered simultaneously: electricity, heating and cooling, gas, and an information grid that serves as a tool for coordination. Defining characteristics of a new grid structure will be a shift from uni-directional to bi-directional operation. Compared to the current centralized structures this implies a decentralized design for electricity generation that blurs the distinction between generation and consumption, a new understanding of thermal grids that integrates the recovery of thermal waste, and an increasing use of current gas grids for biogas and even hydrogen.

Anergy grids for heating and cooling

Such a perspective requires a move from the current structure of separated grids towards integrated structures. This is obvious for the linkage between electricity and heat if thermal processes are involved in the transformation of primary energy. A very innovative development is the design of so-called anergy grids for heat, which typically are operated at low temperatures, e.g. between 15 and 30 degrees Centigrade, and allow the recycling of waste heat, e.g. from sewage water.

The integrating role of these grids

Thus, all elements of the energy system, namely functionalities, application and transformation technologies, including thermal and electric storage devices, will be part of an integrated grid structure and can be seen as a prerequisite for long-term sustainability qualities. In contrast to the prevailing focus on single elements of the energy system the integrated view on supply and demand facilitates balancing the load of the grids. Such an enhanced understanding of the interactions of all components of an energy system in particular allows the integration of the increasing contribution of volatile renewables as photovoltaics and wind. Furthermore, this view offers the opportunity to harvest synergies when moving to low-energy and low-emissions structures. Essentially this is a shift from the traditional concept of economies of scale to the innovative concept of economies of scope.

3.3 Stimulating the innovation of grid structures

From this deepened structural approach to understanding energy systems operational guidelines for the restructuring of energy systems can be developed.

Multifunctional buildings

Buildings should become multifunctional in the sense that it is not sufficient to improve their thermal quality, but it is also essential to make them an active component in the supply and storage of energy. This implies using the physical structure of the buildings as a thermal storage device by integrating thermal exchangers for heating and cooling into the building envelope. In addition, the building foundations can be endowed with thermal storage capacity that can be used even over seasonal periods. Additionally, buildings can provide infrastructure for installing photovoltaics, high-efficient cogeneration units and heat pumps but also storage devices for electricity and heat.

Interlinked mobility

Interlinked mobility promotes an evolutionary understanding of transport by focusing at the services of access to persons, goods, and locations, and the emerging evidence that these services might not always require a transport activity, given the advances in communication technologies. A comprehensive perspective includes zoning concepts that aim for low distances for all activities related to work, personal needs, and leisure. These ambitions might be encouraged by breakthrough technologies, as additive manufacturing, also known as 3D-printing, and holographic communication technologies.

Integrated grids

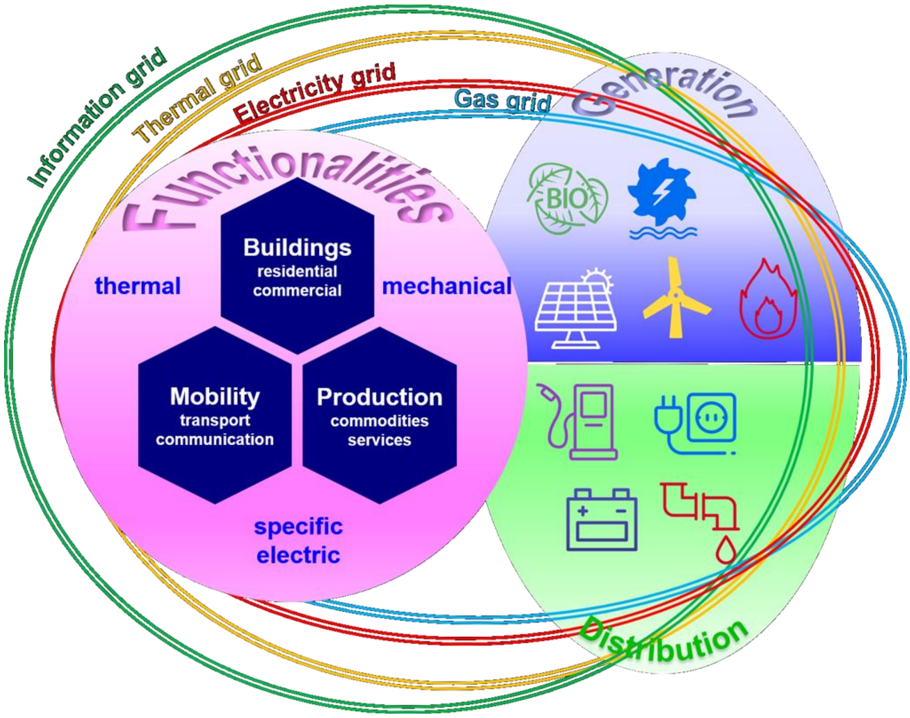
Integrated grids link electricity, heating and cooling, and gas via information technologies that communicate with relevant elements of the energy system, from appliances up to storage devices. Ultimately this would lead to the diffusion of smart grids with the vision of an internet of things. There are still many uncertainties how these integrated grids structures should look like both with respect to their scale and scope but also resilience and data security. An energy system, however, that aims at meeting sustainability qualities, by targeting low-energy and low-emissions for providing the welfare-relevant energy services, will need to give grid structures top attention but at the same time without neglecting vulnerability and resilience aspects of the system.

3.4 Interdependencies of integrated grids

We want to visualize these integrated grid structures with Figure 3 that is inspired by the Swiss Energy Reference Book (Schweizer Energiefachbuch 2016). The core of the energy system are the functionalities to be provided for building structures, mobility and the production sector.

Shown are three energy grids, namely for electricity, heating and cooling, and gas, which operate in a bi-directional mode and are encompassed by an information grid which may link and control any component of the energy system. Several insights arise from these structures which can already be observed in implementations, notably in Switzerland (Bollinger and Evins 2017) and in the United States (IEEE Spectrum 2017). This design is often labelled as micro grid although the term integrated grid gives a better understanding.

Figure 3. Four interdependent grids integrate the energy system



Source: Authors

The coming dominating role of electricity

Typically, the grid for electricity is expected to dominate the whole energy system. Electricity is used for specific functionalities as lighting and electronics but also for motors in appliances and increasingly in mobility and production processes. In line with a prosumer concept, electricity is in addition fed into the grid from locally installed photovoltaic panels or wind turbines in close distance and from a new generation of highly efficient small-scale cogeneration units. Altogether such local electricity grids have the potential of supporting the public grid by load-balancing services.

New storage devices for electricity

The next game changer are the new electric storage devices which promise a similar cost decline as could be observed for photovoltaics over the past ten years. Even the batteries of electric cars could provide storage services when not in motion and linked to the electric grid. An additional feature in this next generation of electric grids could be the link to the thermal grid via cogeneration technologies based on turbines, combustion engines, and fuel cells. Surplus electricity from volatile renewables as PV and wind could be converted via electrolyseurs to hydrogen, which could then be fed into the conventional grid for gas or even put into seasonal underground storage facilities.

Thermal grids with an anergy design

The new thermal grid based on an anergy design can be used for heating and cooling. Sources are thermal solar, heat from cogeneration but also from heat pumps and geothermal sources. Such a thermal grid supplies heat during the winter season and cooling during the summer season.

A new role for gas grids

The redundancy of a full areal coverage of end users in residential or commercial buildings is driving the change in gas grids. Parts of the current grid may be used, however, to transport gas for local cogeneration units and may gradually be fed by gas from biogenic sources like organic waste and even hydrogen.

Smaller scales and localized clustered structures

Altogether Figure 3 shows that an energy system that aims for high energy productivity and low greenhouse gas emissions needs a newly integrated grid design which goes far beyond the current understanding of a smart electricity grid. These innovative grid designs increasingly exhibit smaller scales as well as localized and clustered structures.

3.5 Economic aspects of an integrated energy system

This new shape of the energy system, looked at through the lens of functionalities as delineated above, could be described by the keywords decentralized, clustered and integrated.

Evaluations by the user costs of functionalities

Adopting, however, such a perspective needs to be mirrored in investment decisions and economic evaluation on the one hand and a supporting policy framework on the other. This is particularly true for cost assessments. We stress that the user costs for a specific functionality, composed of annualized capital cost and annual operating cost, are the relevant measure for evaluating any investment decision to arrive at a more sustainable energy system since the user cost of functionalities clearly reflect the combined effect of the investment and operating costs over the whole lifetime of an investment. We also argue that this link of cost considerations to functionalities allows overcoming the often-observable focus on fragmented energy issues, like the substitution of fossil energy sources by renewables, the focus on electricity, e-mobility or any other specific component of the energy system.

Learning from buildings

Buildings are a good example for illustrating the relevance of the user cost of functionalities. Currently housing developers typically expect a return on investment characterized by short-termism that clearly falls short of considering the lifetime of a building and costs over the whole operating period. Consequently, this gives established technologies an advantage over innovative technologies that might have higher investment costs but lower operating costs. Distortions like these would be revealed when focusing on user costs of functionalities.

Transitions without stranded investment

An even more far-reaching perspective is opened by the Paris Agreement [1], which calls for a radical phaseout of greenhouse gases until mid-century. Any current investment based on fossil fuels with a life-time over several decades is exposed to becoming a stranded asset. Energy grids are long-lived infrastructures, their design therefore plays a key role in making a transition to a sustainable energy system possible.

4 Conclusions for policy-makers and research

New perspectives for a fundamental restructuring of the energy system

The new framework for energy analysis as presented here argues that sustainable energy structures require a new perspective and fundamental restructuring of the energy system. A key to this new mindset is the focus on the functionalities to be provided and the deepened structural view of the energy value chain that finally determines the amount of primary energy and the related greenhouse gas emissions. Essential is the integrating role of the grids for electricity, heating and cooling, gas, and information. This raises new research questions in energy economics and energy modeling since many energy and energy-economy models still rely on path dependency of past developments and prevailing structures, thus lacking the potential for analyzing expected radical structural changes.

Overcoming the lack of system thinking

Most currently visible energy policies are characterized by a lack of system thinking and often show a focus on single elements as renewables or electric mobility. Policy strategies focusing on individual components of an energy system may from a comprehensive perspective on sustainability in the worst case even turn out as counterproductive.

A more differentiated argumentation of policy goals and policy instruments

An orientation on long-term sustainable energy systems thus also requires a more differentiated argumentation of policy goals and policy instruments. With respect to buildings e.g., simply focusing on renovation without clear quality standards and an assessment of costs and emissions over the whole lifetime of the building will not meet the requirements of deep structural changes for accomplishing sustainability criteria. A more differentiated argumentation is also needed for single policy recommendations, such as carbon prices. Undoubtedly, carbon pricing is an essential instrument for facilitating changes in the energy system. A uniform price, however, may not meet the requirements for change that prevail in different sectors of an economy.

Thinking in integrated grids provides insights for transformations targeted towards sustainability

Our suggested framework emphasizes that sustainability of an energy system cannot be assessed by single measures, instruments or indicators but only by the interaction of all components ranging from functionalities to primary energy. Thinking in integrated grids is a very operational vehicle to promote such deepened system thinking and reveals that energy system issues need to be mirrored and embedded in broader policy areas like public finance, industrial policy or research policy.

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