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Modelling Low Energy and Low Carbon Transformations

The ClimTrans2050 Research Plan

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Abstract

The ClimTrans2050 research plan provides a framework for modelling long-run transition processes. A deepened structural modelling approach is proposed for the development of a fully operational open source model for Austria. The mindset for the proposed modelling framework rests on a number of innovative aspects: functionalities (shelter, mobility, nutrition, etc.) as ultimate goal of economic activity; stock-flow interactions providing functionalities; distinction of three tiers for modelling (physical, economic and institutional layers). The research plan also lists knowledge gaps and next research steps and addresses how Austrian emissions could be embedded into a global context.

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Executive Summary

The ClimTrans2050 Research Plan provides a framework and research guidelines for the development of a fully operational open source model along the conceptual structure presented above. The open source approach as outlined in ClimTrans2050 has two objectives:

- An interface for the research community in order to provide a platform and transparent information for a stepwise extension of the open source model; and
- a visualisation tool for users such as policy decision makers.

The underlying mindset for such an innovative modelling approach defines a wide range of research efforts as addressed in this research plan. An example for these new research tasks is the need for a coherent modelling of the three tiers and the interactions and feedbacks between them. These research tasks need to be embedded in a simultaneously conducted extension and improvement of existing databases.

We identified in particular the following key features for the next generation of models:

- The focus on functionalities as indicator for wellbeing and economic performance.
- The key element of the modelling framework developed and proposed in this research plan is its focus on wellbeing-related functionalities, ranging from shelter through to mobility (i.e. more precisely access to persons and goods), as the ultimate goals of economic activity. Analysis of transformation processes requires a deep understanding of the structures linking the physical, economic and institutional layers. We therefore start from functionalities and highlight the role of stocks and flows for providing them.
- A deepened specification of the structure of the system, such as the cascade structure in the context of energy and non-energy systems.
- Establishing an open source model for the very long run, and especially for changes in our complex socio-technological system, requires a more explicit representation of the role of technologies, given that these determine the quality of an economy's capital stock.
- Major challenges to modelling economic systems are the need to cover a time horizon over several decades and to deal with significant changes with respect to upcoming breakthrough technologies, disruptive events, social innovations and structural changes. Both issues require a new generation of models that aim at a more deepened structural analysis on the one hand and an explicit representation of the relevant stocks on the other.
- The longer time horizon is motivated by the implications of investments that are made today but determine flows and environmental impacts over their whole lifetime, in some cases over several decades. Such investments relate e.g. to buildings where the building quality determines the amount of energy flows for heating and cooling, or to

mobility where the main influential factors to reduce person kilometres are spatial planning including land use change and infrastructure investments.

- Illustrating this approach we look at the energy system: For transformations which are necessary to achieve the goal of decarbonising the energy system a deeper understanding of the internal structures of systems is needed. A constituting feature of the internal relationships in an energy system is a layer of cascades, starting from energy related functionalities which we name synonymously energy services. We move on via useful and final energy consumption to primary energy flows. We denote this view of an energy system the "Cascade Structure" approach (see also above).
- This perspective of the energy system is fundamentally different from the mainstream focus on energy flows which neglects energy services relevant for wellbeing. Another distinguishing feature for the proposed deepened understanding is the inversion of the sequence of argumentation. Starting point are the energy services and by explicitly considering relevant application and transformation technologies subsequently the energy flows are determined at the respective levels of the energy cascade. A similar example concerns the functionality nutrition for non-energy emissions and is presented in the research plan.
- The separation of the specification of structures from the mechanisms that are generating these structures, in particular non-market based mechanisms.
- Economic activities are embedded into an institutional framework which comprises the regulatory setting that is relevant for coordination and incentives. This includes the role of markets in the private sector and the issue of market failures, which require corrective actions by the public sector (command and control, price instruments) and institutional innovations.
- The model development strategies therefore need to take into account the role of non-market based regulatory instruments in addition to market based instruments. These extended embedding also includes changes in lifestyles, innovative business models and collaborations.

The concept of functionalities in a deepened structural model is made operational along three tiers that are relevant for the sources and the composition of Austrian emissions: the physical, the economic and the institutional tier. Each functionality affects the three tiers and is also affected by them. This underlying mindset (functionalities) and basic structure (three tiers) for modelling builds the basis for analysing transition processes that drive the emissions and the economic system.

The ClimTrans2050 Research Plan aims at providing

- coherent and understandable modelling guidelines that put the focus on functionalities (relating to shelter, access to persons, services and goods, nutrition, etc.) and that stress the interrelationship of stocks and flows in order to provide the functionalities;

- a framework for a deepened structural approach to modelling the Austrian emissions system along a three tier approach that deliberately differentiates between the physical, the economic and the institutional dimensions;
- a modelling framework that allows analysing non-incremental change and transition processes;
- guidance for next steps of research activities following the three tier approach, like modelling feedbacks within the tiers and interactions between them;
- a coherent overall setting that allows to integrate the research activities in a stepwise manner, ultimately arriving at an open-source model that fully covers the Austrian emission inventory in relation to the three tiers.
- In line with the open source approach we provide
- the structure for a web-based platform for exchanging and disseminating information and first model modules to stakeholders and the research community;
- pilot modelling modules based on functionalities and the three tier approach as first milestones of the research steps needed for the open-source model;
- a framework for integrating the Austrian emissions inventory into a global context.

The project team feels that the innovative modelling approach as developed within the project ClimTrans2050 is suitable to be carried on in future research of the project team. The framework for the deepened structural modelling approach is well suited to stimulate discussions in the scientific community on a national and international level as well as with decision makers (policy, administration, social partners, etc.).

The summary of the identified knowledge gaps above indicates, that the development of a comprehensive modelling infrastructure depends on the "cooperation" between researchers and funding institutions in the sense that researchers need to be open minded and funding institutions need to give commitment for midterm funding. The research plan and the proposed modelling framework can be seen as input for the formulation of funding programs and as basis for improved policy advice on long term transition processes.

1 Motivation

The Paris agreement substantiates the immediate need for action to mitigate climate change. The design and development of national climate strategies calls for modelling tools that are able to address long term transformation[1] pathways.

ClimTrans2050 is motivated by the requirement of Austria to design and implement mitigation measures to meet very long term greenhouse gas (GHG) emission reduction commitments. In line with the 7th call of the ACRP, the project focuses on the preparation of a research plan to create an open source model that will allow delineation of emission reduction paths and costs for Austria that would be capable of achieving an 80-95% reduction in GHG emissions by 2050, compared to 1990 levels.

The guiding question for ClimTrans2050 is: What kind of modelling framework is most suitable for assessing the long-term transformation processes needed to drastically reduce Austria's GHG emissions? We propose a framework for an open source model that improves understanding of transformation options and allows their analysis. Our approach for developing this framework was to learn from, but go beyond current modelling paradigms. One central aspect in this context is the introduction of functionalities as target variable of economic activity.

The modelling mindset as developed in ClimTrans2050 results from intense discussions and stepwise clarification of the conceptual foundation. In the development of the framework the project team aimed at a coherent reasoning throughout the research plan. The present document is to be seen as a first step that prepares the implementation of a fully operational open source model for Austria which requires additional time and resources. Transformation options that could be analysed with such an extended modelling instrument would be the ones that are compatible with emerging visions of human lifestyles and economic activities and, additionally, with limiting factors such as GHG emissions.

We contend that such a transformation – be it a shift to renewable resource sources, a substantial increase in energy productivity, or the absolute decoupling suggested between resource use and GDP-related indicators – cannot be understood through a simple extrapolation of current trends.

1.1 A conceptual framework for modelling: Focusing on functionalities

The key element of the modelling framework developed and proposed in this research plan is its focus on wellbeing-related functionalities, ranging from shelter through to mobility (i.e. more precisely access to persons and goods), as the ultimate goals of economic activity. Analysis of transformation processes requires a deep understanding of the structures linking the physical, economic and institutional layers. We therefore start from functionalities and

[1] Throughout this report we use the terms "transition" and "transformation" as synonyms. We are aware that there is literature that discusses the difference between these two terms.

highlight the role of stocks and flows for providing them. Establishing an open source model for the very long run, and especially for changes in our complex socio-technological system, thus requires a more explicit representation of the role of technologies, given that these determine the quality of an economy's capital stock.

The ClimTrans2050 Research Plan proposes a new perspective on emissions and economic structures as well as the accompanying institutional framework and identifies next steps for research for the implementation of a fully operational open source model for Austria. This is complemented by exemplary model modules and an interactive web platform. It is the first step for the development of an operational open source model based on the proposed new understanding of modelling transformation processes. In this sense the research plan provides manifold suggestions and broad basis for further research.

1.2 The structure of the report

We coin the mindset followed in the ClimTrans2050 Research Plan a deepened structural modelling approach as foundation for a fully operational open source model for Austria that is suitable for modelling long run transformation[2]. Besides establishing a general modelling framework the ClimTrans2050 Research Plan identifies the necessary next research steps for its implementation. The report is structured as follows:

- In chapter 2 the foundations and underlying mindset of the proposed deepened structural modelling approach for long-run transformation processes are formulated. This encompasses the introduction and definition of the new terminology used for the deepened structural modelling approach. The proposed modelling structure rests on three tiers, the physical, economic and institutional layer. The chapter ends with a summary of the key characteristics for a new open source model and its necessary elements for implementation.
- The challenge to avoid dangerous climate change is a global issue which can only be addressed by worldwide concerted action on national and local levels. Therefore, any national policy aiming at fostering transition from a carbon-intensive to a low carbon economy, in order to have the desired impact on the climate, must be consistent with global emissions reductions targets. Chapter 3 provides a framework for embedding emission scenarios for Austria in a global context and presents open research tasks in this global context.
- The concept of the physical layer of the deepened structural modelling approach as elaborated in chapter 2 is transferred to energy and non-energy emissions in chapter 4. Chapter 4.1 presents a widely advanced pilot model module for the energy system. Chapter 4.2 presents considerations and basic approaches for the modelling of

[2] Although we focus here on Austria, in principle the conceptual modelling framework could also be transferred to other countries.

emissions from non-energy sources. Both chapters end with a list of necessary research steps for implementing an operational open source model.

- The modelling mindset for the economic layer is set out in chapter 5. The focus is put on user costs (including both operating and investment costs) since only they allow a comprehensive assessment of options. In addition the economic layer needs to cover macroeconomic effects, both of the investment and operating phase.
- In chapter 6 the institutional layer (policies and instruments) is presented that addresses the framework that influences stocks and flows which may induce a change in the physical and economic layer.
- The implementation of a fully operational open source model should be accompanied by the setup of an easily accessible web platform. ClimTrans2050 provides exemplary model modules integrated in a web based platform. The access to the web platform and the exemplary model modules is facilitated by a model manual. The web platform, exemplary model modules and the model manual are subject of chapter 7.

2 An enhanced modelling approach for transition strategies

For analysing radical transformations towards a low emission society a deepened structural analysis[3] is needed that provides policy guidance for long run transition processes. The need for advancement in modelling in the context of climate change and long-run transformation has increasingly gained attention. The limitations of current modelling has been addressed e.g. by Pindyck (2012, 2013, 2015), Stern (2016), Rosen and Guenther (2015). However, any advancement or proposal of an extended modelling framework should reflect on current modelling practices.

In the following we present in a stylized way mainstream (energy) modelling approaches as well as a summary of a meta-analysis of their strengths and weaknesses. With this background we elaborate an extended mindset for modelling.

2.1 The limits of current mainstream approaches

Current economic paradigms and the related modelling approaches focus mainly on economic activities related to flows in a given time period, such as a quarter or a year. These models concentrate on goods and services which we coin 'reproducibles'. Reproducibles are the outcome of production activities that are used for final and intermediate consumption as well as investment. The production of reproducibles in mainstream economic models implicitly makes use of manmade and natural capital stocks in terms of flows. Details on the volume and quality of as well as changes in stocks, however, are often not modelled explicitly. Omitting stock characteristics in evaluating the consequences of economic activities is critical in particular for long-run analyses where the overuse and limits of resources (stocks) might become evident.

Prices and substitution elasticities strongly affect the supply and demand structure of reproducibles in mainstream economic models. Substitution typically prevails between different factors of production (e.g. labour, capital, energy). Also on the demand side substitution elasticities determine the bundle of consumer goods and services for a given income level. Technological progress typically takes the form of incremental productivity improvements and thus shows strong path dependency. This implies also a limited ability to deal with disruptive technological change like a shift towards decentralized electricity generation which could mean a rapid diffusion of PV panels in combination with storage technologies.

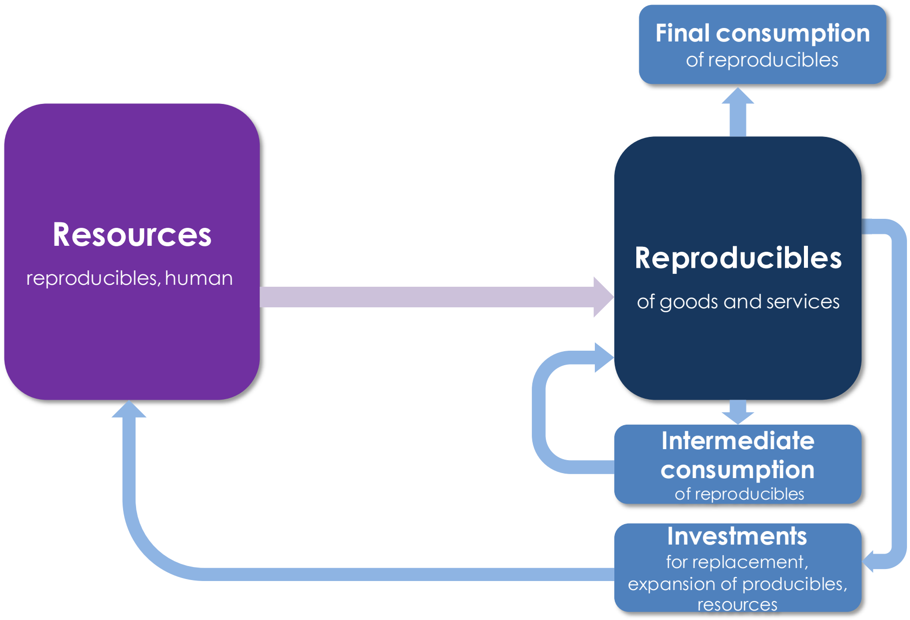
In Figure 1 we indicate the stylized structure of mainstream modelling approaches. Key elements are flow components which put the volume of reproducibles into the centre of reasoning and investigate both their supply and demand. Supply considerations look at the availability of resources, mainly labour and investments in capital (such as buildings and

[3] We name the modelling approach put forward in this research plan "deepened structural modelling" as framed in the following.

machinery) needed for the production of reproducibles. The volume of reproducibles is used for final and intermediate consumption and for investments. Feedbacks of economic activities on stocks are not sufficiently dealt with. This holds both for manmade capital and other resources as natural capital.

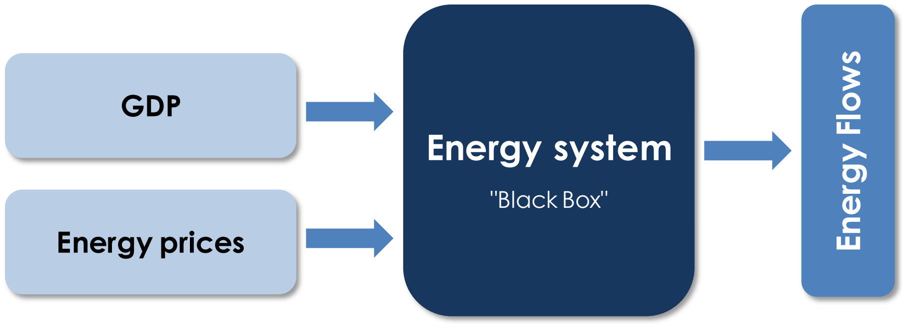
At least two conclusions emerge from this view on economic activities that motivate searching for enhanced modelling approaches in particular for evaluating long-run perspectives of economic development: First, the focus on the volume of reproducibles of a certain period as an indicator for economic performance, and second, the rather neglected role of the stock of resources.

Figure 1 The mainstream approach to modelling economic activities



Similar considerations hold for the analysis of energy systems. Almost all mainstream modelling approaches of energy systems relate some causal inputs (typically economic activity like GDP and factor prices) to energy flows. The parameters describing the related transfer functions originate from specified technologies, econometric estimates or a general equilibrium specification. We coin these modelling designs as depicted in Figure 2 "Black Box" approaches, since they do not reveal the complex internal structure of an energy system.

Figure 2 The "Black Box" approach to energy systems



2.2 Lessons learned from existing modelling practices

In the following we summarise the results of a meta-analysis of the strengths and weaknesses of current energy modelling practices that are presented in detail in ClimTrans2050 Working Paper No.1 (Schinko et al., 2015) and which is attached in the Appendix. For the most common state of the art energy modelling approaches a critical and systematic review has been conducted, describing the approaches and giving insight into the respective strengths and weaknesses with special regard for long-term transition analyses.

Existing energy- and climate-economic modelling approaches are increasingly seen with scepticism regarding their ability to forecast the long term evolution of economies and energy systems. The economic, climate and energy sphere are highly complex non-linear systems, so far most often only poorly dealt with when assessing the transition pathways leading to a desirable future. Schinko et al. (2015) report a structured meta-analysis of state-of-the-art national and international energy-economic modelling approaches, focusing on their ability and limitations to develop and assess pathways for a low carbon society and economy, both in total and for the main sectors contributing to greenhouse gas emissions. In particular, the paper sets out to identify those existing models and/or model components/modules which could be of interest in developing a research plan for the creation of an open source model for analysing a national transition to a low carbon society by 2050, here more specifically applied to Austria.

It is found that existing methodological approaches have some fundamental deficiencies that limit their potential to understand the subtleties of long-term transformation processes. Most modelling approaches that were analysed (specifically econometric, computable general equilibrium, and New Keynesian approaches) are characterised by an almost complete absence of details of the energy cascade[4], in particular they lack to model the central role of functionalities that are provided by the interaction of energy flows and corresponding stock variables. Further they are not well equipped for analysing radical

[4] The concept of the energy cascade plays a central role for the modelling framework in ClimTrans. The concept is elaborated in detail in chapter 4.1.

technological changes. Model results often depend on only a single mechanism depicted by the modelling approach, e.g. for computable general equilibrium models, partial equilibrium models or New Keynesian models (relative) price changes are the key drivers. Reversely, top-down integrated assessment models (IAMs) aim to include as many mechanisms as possible and are hence capable of capturing feedback effects between aspects of the system under consideration (economy, climate system, society, other environment). This however comes at the cost of either (a) working on a very coarse level of detail, with e.g. only limited explicit representation of alternative technologies and using highly uncertain (e.g. damage-) functions between relating e.g. economic indices like a region's GDP and global mean temperature changes (hard-link IAMs) or (b) experiencing problems in convergence and consistency among the models used (soft-link IAMs). Bottom-up, partial equilibrium optimization models investigating energy systems are capable of depicting a rich technological detail and of identifying technologically optimal solutions (as defined by an objective function) and hence rule out inferior solutions. However, due to high computing requirements these models are limited to restricted complexity (e.g. convexity and missing macroeconomic feedbacks) and are therefore less suited to evaluate realistic forecasts of energy system states which are far from the optimal solution as defined by the objective function, which is usually the case for real-life systems. Comparatively novel methodological approaches such as System Dynamics (SD) or Agent Based Models (ABM) do allow for representing stock-flow relationships and dynamic, disruptive transformation processes but lack the possibility to find optimal pathways (e.g. least cost, minimizing energy demand, minimizing emissions) for the transition and tend to be highly resource intensive regarding empirical data input, which is, however, critical for deriving real world relevant results. Moreover for SDs and ABMs, just as for more traditional approaches such as computable general equilibrium approaches, problems might occur regarding the separation of the structure – e.g. the elements of an energy system – from the mechanisms that are generating these structures (e.g. policy instruments). What is true for all modelling techniques is that the results are heavily driven by exogenous input (parameter) assumptions (e.g. price elasticities, perfect information, rational behaviour of agents, model closures) which are in turn triggering endogenous responses within the model.

Based on this meta-analysis we suggest that a methodological framework for analysing long-run transition processes has to move beyond current state of the art techniques and simultaneously fulfil the following requirements: (1) inherent dynamic analysis, describing and investigating explicitly the path between different states of system variables, (2) specification of details, in particular of the central role of functionalities that are provided by the interaction of flows and corresponding stock variables, (3) a clear distinction between structures of the energy/emission/economic systems and (economic) mechanisms and (4) ability to find feasible pathways (e.g. reflecting both the investment and the operating phase). Furthermore, a crucial early task in modelling is to specify explicitly which of the model elements are determined endogenously, and which exogenously, ideally governed by the demands of the underlying question to be answered.

2.3 Challenges and elements for understanding structures and emissions

The development of a deepened structural modelling approach of the economic and emission system as motivated above requires a different generation of modelling activities that rests on a new mindset and understanding compared to mainstream modelling.

The idea of a deepened structural modelling approach, as laid out in the following, provides the basis for the ClimTrans2050 Research Plan. This research plan proposes a stepwise development of a fully operational open source model based on a deepened structural approach. To this end a suitable general model structure is explored that ultimately will be able to capture the entire greenhouse gas inventory on the one hand and to explore the socio-economic implications on the other. The model framework will depict the whole chain from functionalities to greenhouse gas emissions.[5] To ensure the feasibility and suitability of the proposed modelling architecture, pilot modelling modules are explored and implemented in an open source setting.

For long term analyses of decarbonised structures 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, as is GDP as measure for wellbeing (e.g. Stiglitz et al., 2009). The present research plan therefore seeks to promote the concept of functionalities as ultimate purpose of economic activity.

Functionalities are defined as the result of the interaction between stocks and flows to serve (basic) human needs such as shelter, e.g. the thermal experience in buildings results from the quality of the building stock and the related energy flows. Another example would be mobility, that from a functionality perspective is the access to persons, goods and services, and that can be provided by different spatial allocations of industrial and settlement locations, transport technologies, transport modes or in some cases by communication technologies.

Traditional approaches to analyse energy and emission systems mainly focus on energy flows or other flows that generate GHG emissions whereas a modelling approach introducing functionalities strongly emphasises stocks of all kinds.

Model analysis that provides policy guidance on transformation towards economic structures that meet the long term greenhouse gas emission reduction targets needs to illustrate the impact of disruptive technologies. This goes beyond capturing incremental technological progress mainly driven by changes in (relative) prices as in a large number of existing models.

[5] While this section supplies an overview, the deepened structural modelling approach is described in more detail in chapter 2.4.

A deepened structural modelling approach illustrates the interaction between capital stocks (including technologies they represent) and flows in order to provide a specific functionality.

The diffusion and use of technologies that are characterised by disruptive change impacts the emission system on the one hand and shapes economic structures on the other. Disruptive change, from an analytical point of view, can arise with a shift of the focus from economies of scale – i.e. cost reductions with increasing scales of production – to also consider economies of scope, that means acknowledging that any choice can be connected to implications at a multitude of dimensions, e.g. for the energy system integration on all levels of the energy system (functionality supplied, use, supply). Such changes strongly concern and affect investment decisions that – in this new setting – result from an integrated view of the energy system or new options for decentralized structures. Changes also concern – they trigger or are triggered by – changes in behaviour, llifestyles, social practices, or business models.

2.4 A deepened structural modelling approach for long-run transformation processes

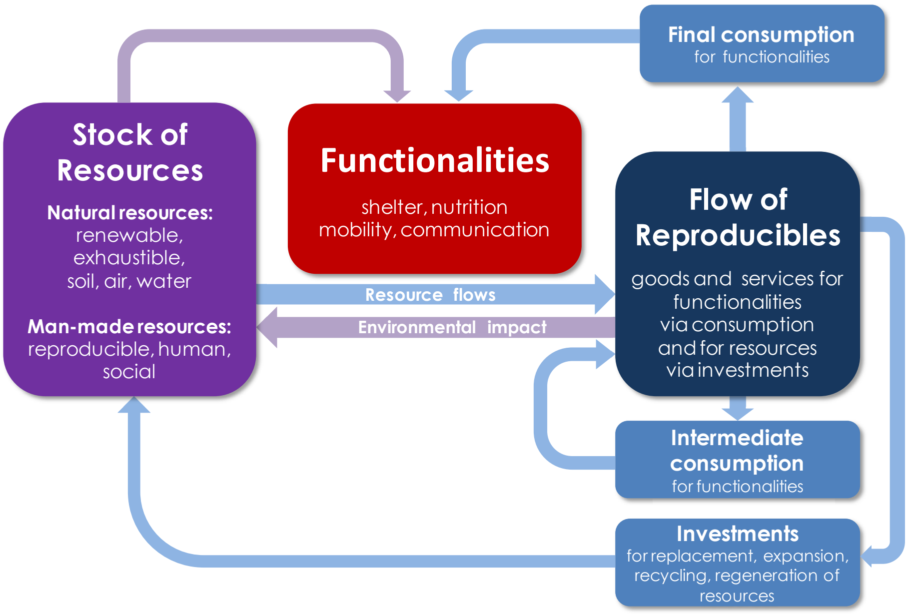
2.4.1 Principle of a deepened structural modelling approach

Major challenges to modelling economic systems are the need to cover a time horizon over several decades and to deal with significant changes with respect to upcoming breakthrough technologies, disruptive events, social innovations and structural changes. Both issues require a new generation of models that aim at a more deepened structural analysis on the one hand and an explicit representation of the relevant stocks on the other.

The longer time horizon is motivated by the implications of investments that are made today but determine flows and environmental impacts over their whole lifetime, in some cases over several decades. Such investments relate e.g. to buildings where the building quality determines the amount of energy flows for heating and cooling, or to mobility where the main influential factors to reduce person kilometres are spatial planning including land use change and infrastructure investments.

These deliberations motivate a deepened structural framework for a more comprehensive understanding of economic activities which is depicted in Figure 3.

Figure 3 A deepened structural approach to modelling economic activities



Compared to the mainstream approach as indicated in Figure 1, five extensions become visible in Figure 3:

- First, the notion of functionalities as purpose of any economic activity.
- Second, the emphasis on the role of the stock of resources (not only reproducible and human resources, but also renewable and exhaustible resources) for the flow of reproducibles.
- Third, the interactions of the stocks of resources and the flow of reproducibles for providing functionalities.
- Fourth, the direct relevance of stocks for functionalities.
- Fifth, the environmental impact of economic activity on the extended stock of resources.

Increasingly the adequacy of GDP as current measure of economic performance is questioned. The call for measuring economic performance that goes beyond GDP is supported by the need to account for environmental boundaries and fundamental transformation processes (see also Kettner et al., 2014). Responding to this discussion we emphasise the role of functionalities as a more relevant indicator for well-being.

Long-run considerations of economic development are highly dependent not only on the volume of resources as human and reproducible capital stocks but also on the natural capital stock like exhaustible and renewable resources (including water, soil and atmosphere).

One major aspect of the deepened structural modelling approach is the emphasis on the proposition that functionalities result from the interaction of flows from reproducibles and stocks of an extended list of resources. This is the core element of the concept relevant for different functionalities.

Figure 3 visualises the central aspects and their interactions. Three distinctive categories are of importance: Functionalities, stocks of resources and flows of reproducibles. The volume and composition of functionalities needed or desired determines the volume and composition of reproducibles (goods and services). Flows of reproducibles are either used as intermediate consumption in the production of goods and services or they represent one component for providing functionalities via final consumption. Functionalities result from the interaction of the stocks of resources with the flows of reproducibles.

Via investment, reproducibles (e.g. buildings, cars, machinery) flow into the stock of resources, changing either its volume or quality.

The rationale of the interdependence between the stock of resources and the flow of reproducibles is crucial since a specific functionality can be satisfied with a varying combination of stocks and flows. In the context of the functionality shelter e.g. for a specific room temperature a higher flow of energy is required in the case of a low quality of the building stock or vice versa.

In the context of transformation processes the role of breakthrough or disruptive technologies becomes evident as their diffusion would impact the flow of reproducibles in order to serve functionalities. Investments in such innovative technologies (zero energy and plus energy houses, new materials and processes in the production sector such as biorefineries, alternative agricultural processes such as extensive agriculture, …) have the potential of fundamentally changing our energy and/or emission systems compared to conventional investment decisions. Complementary to innovative technologies social innovations and behavioural change (dietary habits, changes in mobility behaviour or in product use like the avoidance of stand by functions) may contribute significantly to a transformation of energy, emission and/or economic systems.

2.4.2 The focus on functionalities

Following different strands of research that aim at enhancing economic analysis and modelling with a focus on wellbeing, the ClimTrans2050 Research Plan and the proposed modelling framework for an open source model focus on energy or emission relevant functionalities[6], as already referred to above, as the ultimate goal of economic activity.

> ***Functionalities*** *(e.g. nutrition, shelter, access to goods, services and people)* as understood in the context of this research plan are defined as ***the outcome of the interaction of stocks*** *(e.g. buildings and machinery)* ***and flows*** *(e.g. energy and materials)*.

[6] Other functionalities are e.g. health, quality food or nature protection. Also for these functionalities the challenge of quantification applies.

In addition to end-use functionalities (as relevant for the wellbeing of persons) the concept implicitly also includes intermediary functionalities for reproducibles (as goods and services).

Functionalities can cover comprehensive areas like shelter, nutrition or access to goods, services and people (mobility), or supportive energy related functionalities such as thermal, mechanical or specific electric functionalities, when the energy system is analysed in more detail.

In order to illustrate the principle of functionalities, Table 1 shows three examples (shelter, mobility, nutrition) that are relevant for emissions. These main categories can be understood as the sum of more concrete supportive functionalities.

Table 1 Illustrative examples for a specification of functionalities

Functionality	**Supportive functionality**	**Description**
Shelter	*Low temperature heat*	Space heating and cooling
	Specific electric	Lighting, electronics
Mobility (access to goods, services and people)	*Mobile engines*	Transport
	Specific electric	Communication
Nutrition	*Calorie demand;* *Carbohydrate production;* *Protein production*	E.g. grain production, meat production

The concept of functionalities for obtaining a better understanding of the energy/emission and economic system and its development over time contains the following elements. Functionalities

- aim at capturing the ultimate purpose of economic activities,
- emphasise the interaction between stocks and flows in an economy,
- can be related to the physical, economic and institutional tier,
- relate to both the consumption and production side of an economy,
- allow capturing the impact of the investment and operating phase, and
- point to details of technologies and are therefore suitable for evaluating transformation processes and disruptive technological changes.

The focus on functionalities and the interaction of stocks and flows, as outlined above for the deepened structural model, shape the proposed basic structure of the framework for an open source model for Austria in the ClimTrans2050 Research Plan.

In the following we discuss the relevance of the interaction of stocks and flows for providing functionalities in more detail.

Figure 4 Relevance of stocks and flows for providing functionalities

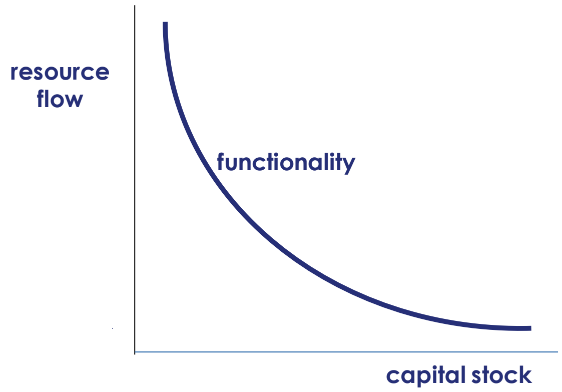


Figure 4 illustrates that a specific functionality is the result of resource flows and capital stocks. All points along the graph represent the same level of a specific functionality that is provided by a combination of the capital stock and resource flows. Along the curve to the right are those combinations where a larger capital stock (in the case of mobility e.g. more public transport) or a capital stock of higher quality requires much less resource flows for the provision of the functionality.

2.4.3 The three basic tiers in a deepened structural model setting

The concept of functionalities in a deepened structural model is made operational along three tiers that are relevant for the sources and the composition of Austrian emissions: the physical, the economic and the institutional tier. Each functionality affects the three tiers and is also affected by them. This underlying mindset (functionalities) and basic structure (three tiers) for modelling builds the basis for analysing transition processes that drive the emissions and the economic system. One of the main challenges of implementing and developing a deepened structural modelling are additional data requirements.

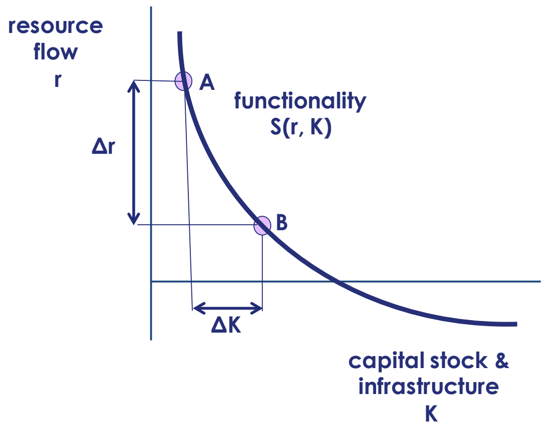
Tier 1: The physical layer

Tier 1 addresses the physical layer of the modelling approach. It represents the interaction of the stock of resources and the flow of goods and services which provide the welfare relevant functionalities. These interactions cause impacts on resources, in particular on the level of emissions in air, water and land.

The insight gained from modelling the details of the physical structure will allow evaluating the impact of changes in technologies (stocks) – above all also disruptive changes – on emissions.

In Figure 5 the impact of the substitutability between stocks and flows in order to provide the same level of functionality is depicted. As already illustrated in Figure 4, along the curve the same level of a specific functionality is provided. This functionality (S) results from the use of capital stocks and resource flows S(r, K) as indicated in the figure. Movements along the curve e.g. from A to B illustrate the substitution between stocks and flows, with Δr in this case the reduction in resource flows that results if the change of ΔK in the capital stock is realized. In some cases resource flows might even become negative e.g. in the case of energy plus buildings that generate more energy than they consume. In the case of ClimTrans2050 we focus on emission relevant resource flows, so that changes in resource flows translate into changes in emissions.

Figure 5 The impact of the substitutability of stocks and flows



Illustrating Tier 1 for energy, a comprehensive functionality like shelter is supported by specific energy related functionalities as thermal, mechanical, or specific electric for lighting and electronics. This also holds true for other categories of functionalities, as mobility or communication.

It is then the energy flows (disaggregated by energy sources) in the energy use categories that are of interest and finally the transformation and supply mix of primary energy. Essential for the amount of energy flows needed is the choice of application and transformation technologies (stocks) along the whole energy cascade as well as behavioural change. The flows of energy and the energy mix finally determine the amount of related emissions. The detailed description for the energy systems follows in chapter 5.1.

With respect to nutrition we take agricultural production of nutrients as an example. Here the capital stock would be agricultural soil and the flow of reproducibles would be the crop yield. The output can be increased by applying fertilizers or by providing irrigation in dry regions;

thereby either increasing the crop yield or decreasing the area needed to produce a certain yield. An example for the capital stock relating to stock-farming would be dairy cows. Obtaining a breed yielding more milk per cow would result in less area for stables to get the same amount of milk. However, methane emissions from milk production are always closely related to the overall yield. The main trigger for reducing emissions is to replace milk by other, less emission-intensive products.

This assessment requires collecting information about the structure and quality of the existing capital stock for providing a specific functionality, e.g. housing stock differentiated by thermal quality or the number of wind turbines of a specific generating capacity. The installed capital stock determines the current operating, maintenance or replacement activities resulting in corresponding expenditures and investments.

Tier 2: The economic layer

Tier 2 is dealing with the socio-economic and techno-economic structure by assessing stocks and flows related to specific functionalities. Tier 2 translates (changes in) the physical structure underlying the functionalities into economic activities and costs.

The economic model structure needs to distinguish the effect of transformation options on different levels of the emission system, i.e. the amount of functionalities desired, flow impacts and stock impacts.

The knowledge of the quality of the existing capital stock including infrastructure and the related flows is the basis for the (macro-)economic evaluation of transformation processes towards low-emissions structures. Related investments and operating costs influence diffusion paths of innovative technologies. The (macro-)economic evaluation of transformation options reflects the change of the current stock and the respective changes in flows that result from investment in stocks, e.g. investment costs in order to improve the thermal quality of the building stock are related to reduced energy flows for heating. The impact on flows can be observed over the whole lifetime of the building.

The overall macro-economic impacts (changes in intermediate consumption, employment, etc.) of different transformation options need to be captured in the economic layer. Again this comprises the investment and the operating phase. The economic evaluation of the investment phase has to account for the changes in intermediate consumption due to new technologies, i.e. disruptive technologies might significantly change the input output structure of an economy. This may be true for the investment as well as the operating phase. While the economic effect resulting from investment demand is limited to the investment phase, the economic impact of the transformation option in the operating phase depends on the lifetime of the technology.

Macroeconomic models are needed that can capture the interlinkages across economic sectors and agents and which explicitly illustrate the different impact of investment and operating. Input-output modelling for the macroeconomic analysis of the transition allows capturing the complex interrelations within the economic system. It can translate technological change into system-wide economic impacts via changes of the underlying production coefficients. In addition this approach is relatively easy manageable with respect to modelling effort and data requirements and thus it is also in line with the target to build up an open source framework.

Tier 3: The institutional layer

Economic activities are embedded into an institutional framework which comprises the regulatory setting that is relevant for coordination and incentives. This includes the role of markets in the private sector and the issue of market failures which require corrective actions by the public sector (command and control, price instruments) and institutional innovations.

The model development strategies therefore need to take into account the role of non-market based regulatory instruments in addition to market based instruments. These extended embedding also includes changes in lifestyles, innovative business models and collaborations.

Framing an economic model by differentiating these tiered components offers a number of insights.

- First, it allows differentiating physical interactions and their economic representation in monetary units.
- Second, it separates the description of economic structures from the mechanisms which impact those structures.[7]
- Third, a variety of market and non-market based mechanisms can be considered.
- Fourth, details in technologies which might be relevant for describing and evaluating transformation processes can be captured.

This deepened structural modelling approach is strongly motivated by the need of extending the time horizon of economic analyses. This holds in particular for the exploration of low carbon structures up to time spans ranging half a century or a century ahead. This challenge requires a conceptual framework which is able to cope with disruptive changes that result in structural breaks.

2.5 The innovative aspects of the ClimTrans2050 Research Plan in a nutshell

The ClimTrans2050 Research Plan provides a framework and research guidelines for the development of a fully operational open source model along the conceptual structure presented above. The open source approach has two objectives: An interface for the research community in order to provide a platform and transparent information for a

[7] The structures depict e.g. the impact of technologies on emissions but also related investments and operating expenditures. This is differentiated from mechanisms that influence e.g. the choice of or the diffusion rate of new technologies like economic instruments or command-and-control regulation.

stepwise extension of the open source model; and a visualisation tool for users such as policy decision makers.

The underlying mindset for such an innovative modelling approach defines a wide range of research efforts as addressed in this research plan. An example for these new research tasks is the need for a coherent modelling of the three tiers and the interactions and feedbacks between them. These research tasks need to be embedded in a simultaneously conducted extension and improvement of existing databases.

We identified in particular the following key features for the next generation of models:

- The focus on functionalities as indicator for wellbeing and economic performance.
- A deepened specification of the structure of the system, such as the cascade structure in the context of energy and non-energy systems.
- The separation of the specification of structures from the mechanisms that are generating these structures, in particular non-market based mechanisms.

2.5.1 *Elements of the research plan*

The ClimTrans2050 Research Plan aims at providing

- coherent and understandable modelling guidelines that put the focus on functionalities (relating to shelter, access to persons, services and goods, nutrition, etc.) and that stress the interrelationship of stocks and flows in order to provide the functionalities;
- a framework for a deepened structural approach to modelling the Austrian emissions system along a three tier approach[8] that deliberately differentiates between the physical, the economic and the institutional dimensions;
- a modelling framework that allows analysing non-incremental change and transition processes;
- guidance for next steps of research activities following the three tier approach, like modelling feedbacks within the tiers and interactions between them;
- a coherent overall setting that allows to integrate the research activities in a stepwise manner, ultimately arriving at an open source model that fully covers the Austrian emission inventory in relation to the three tiers.

2.5.2 *From concept to implementation*

In line with the open source approach we provide

- the structure for a web-based platform for exchanging and disseminating information and first model modules to stakeholders and the research community;
- pilot modelling modules based on functionalities and the three tier approach as first milestones of the research steps needed for the open source model;

[8] The three tier approach is developed in more detail in the following chapters.

- a framework for integrating the Austrian emissions inventory into a global context.

In the remainder of the document the integration of Austrian emission pathways into a global context is set out in more detail. This is followed by a comprehensive description of the three tiers of the modelling framework. At the end of each chapter the next steps for research and implementation are formulated. How the open source model could be implemented and accessed by users is described along exemplary model modules in the last chapter where also information on the web platform that already is available is provided.

3 National GHG emissions in a global context

3.1 Motivation

Climate change is a global issue which can to be addressed only by worldwide concerted action on national and local levels. Therefore, any national policy aiming at fostering transition from a carbon-intensive to a low carbon economy, in order to have the desired impact on the climate, must be consistent with global emissions reductions targets.

The Paris climate change conference (COP 21) in December 2015 resulted in an international agreement pledging to limit the increase of the global mean temperature to 2°C above pre-industrial level. This important political declaration sets the objectives for global climate action, yet the means and strategies of achieving them still remain an open question. The functionality–based approach to modelling economic transitions proposed in this research plan is designed to help identify feasible scenarios of transition to a low carbon economy which is essential if we want to meet the 2°C warming target. The approach introduced below provides a consistent framework for translating the overall ambition of limiting global warming to national carbon budgets.

3.2 From the budget of cumulative global GHG emissions to national emissions reductions targets

The formulation of national climate policy which is consistent with a globally assumed warming target requires the two following steps: 1) Specifying global GHG emissions constraints corresponding to an assumed warming target; and 2) Distributing efforts of global climate action among nations. An extended version of the Emissions-Temperature-Uncertainty (ETU) framework (Jonas et al. (2014), see also Appendix B.1) provides the means to address both these problems.

3.2.1 Global emissions constraints

The concept of a budget of cumulative global GHG emissions over a certain period is the key to understanding what any assumed warming target means in terms of required global GHG emissions cuts. In the work of Meinshausen et al. (2009) it has been shown that the cumulative emissions in the period 2000 – 2050, rather than emissions in any individual year within this period, are a good predictor of a stabilisation level of global warming after 2050 (with respect to pre-industrial period). The ETU framework builds on this finding. In short, it allows us to translate a global warming target (e.g. 2°C above the mean global temperature in the pre-industrial period) into cumulative global GHG emissions until 2050. Knowing this budget and the present level of emissions we are able to derive the rate of required reductions as well as the target level of global GHG emissions in 2050 (see Figure 6a and Appendix B.2 for further details). However, we emphasise that these emissions reduction targets were obtained under strong assumptions about the Earth-climate system. Among others, we assume that there will be no catastrophic systemic surprises (such as massive melting of permafrost) in the future, and that the Earth system will eventually return to its equilibrium from before the industrial revolution. . If these assumptions turn out not to be valid, even more severe emissions reductions could be required and the outcome of climate action would become yet more uncertain. For details on the ETU framework assumptions see Appendix B.1.

3.2.2 Derivation of national emissions reductions targets

The step from global to national emissions reductions targets requires a guiding principle for assigning fractions of the cumulative GHG emissions budget to specific countries. As many of such principles are conceivable, the ETU framework is based on the principle of global per capita GHG emissions equity in 2050 (meaning that in 2050 the limit of emissions required to support living and wellbeing of any individual will be equal for anyone, regardless of his/her nationality, age, etc.). The merit of this principle is that it provides targets for per capita emissions in 2050 that are easy to understand, and are universal and meaningful at any scale (from global through national to local).

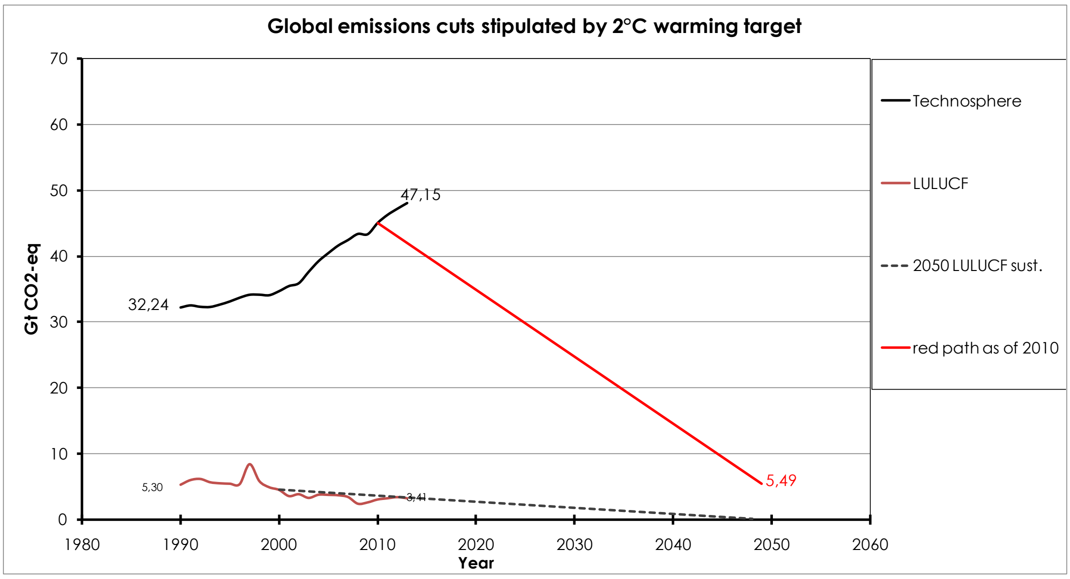
We calculate the abovementioned limit of per capita emissions by dividing the global emissions target in 2050 by projected world population in 2050[9]. An exemplary global per capita emissions equity target corresponding to pledge of keeping global warming below 2°C is presented on Figure 6b (For further details see Appendix B.2).

The equitable 2050 per capita GHG emissions limit may be used directly as the objective of a national emission reduction policy (e.g. linear reductions of per capita emissions, see Fig. 7b). It could also be used to derive reductions requirements for total national GHG emissions by multiplying the per capita emissions target by future population projection (see Fig. 7a). The budget of cumulative emissions until 2050 corresponding to the assumed warming target is calculated as an area under the line connecting present national emissions with the 2050 target. (For further details on the method of deriving of national targets see Appendix B.3.)

[9] UN Population Division: http://esa.un.org/unpd/wpp/DVD/

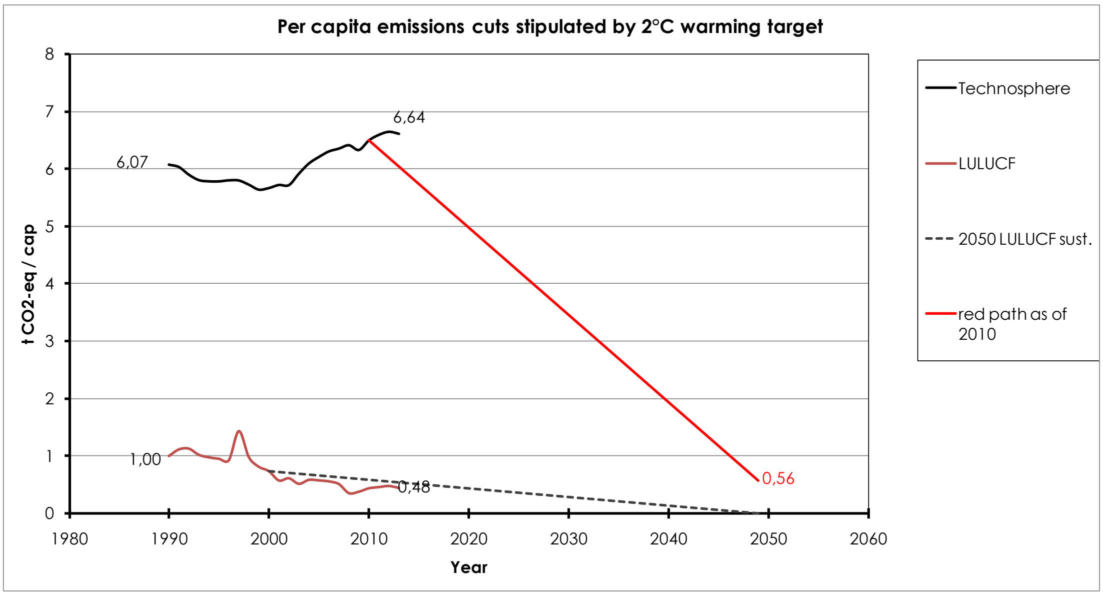
Figure 6 Cuts in global GHG emissions required to meet a 2°C warming target

- Absolute[1])



[1]) Emissions cuts demanded by 2°C warming target in terms of total global GHG emissions. The black line represents historical technospheric GHG emissions. The brown line represents emissions related to land use, which we assume to be sustainable in 2050 (gray dashed line). The red line is a linear reduction target path required to meet 2°C warming target if reduction efforts were undertaken in 2010. However, as emissions between 2010 and 2014 did not follow the assumed linear reduction path, the reduction needs to be even steeper in the following years.

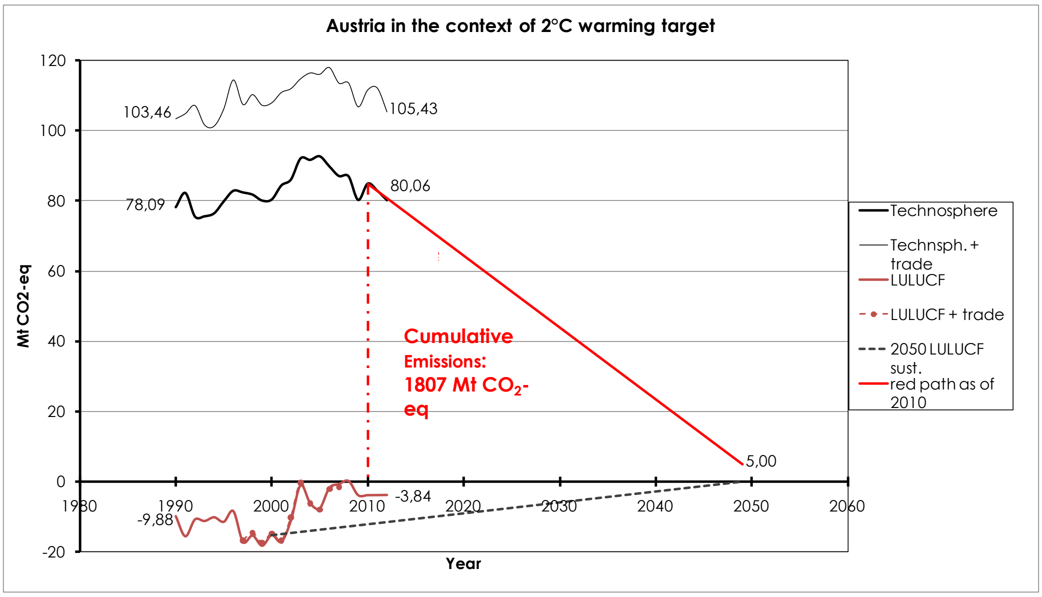
- per capita[1])



[1]) As on Fig. 6a but in per capita terms.

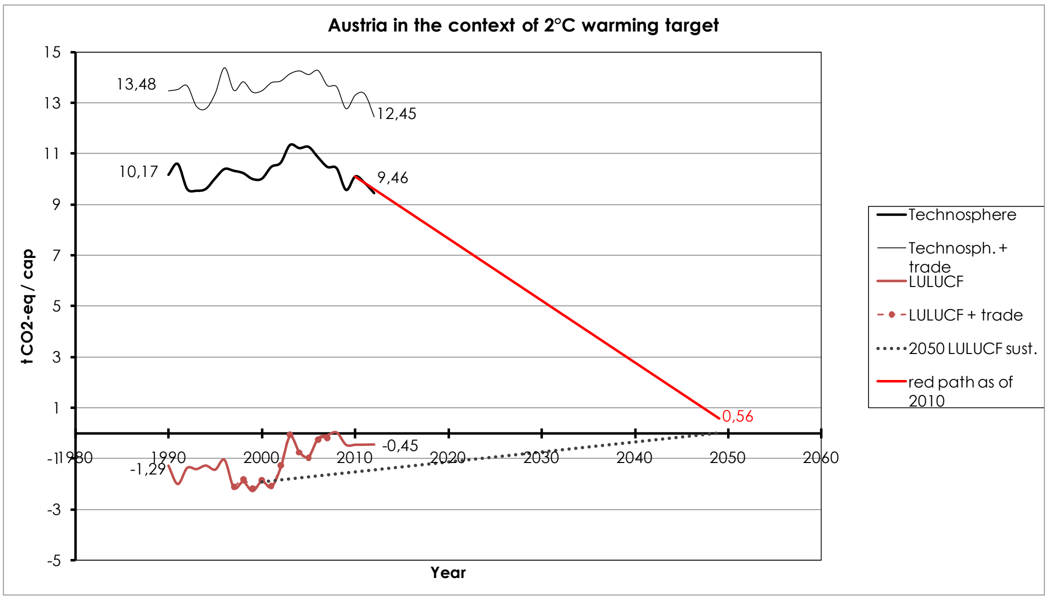
Figure 7 Austria's GHG emissions reductions requirements consistent with 2°C warming target

- Absolute[1])



[1]) The thick black line represents historical territorial technospheric GHG emissions (production-based perspective) while the thin black line shows technospheric emissions taking into account international trade and embodied emissions of goods consumed on Austrian territory (consumption-based perspective). The brown line represents emissions from land use, which we assume to be sustainable in 2050 (grey dashed line). The red line is a linear reduction target path required to meet 2°C warming target if reduction efforts were undertaken in 2010.

- per capita[1])



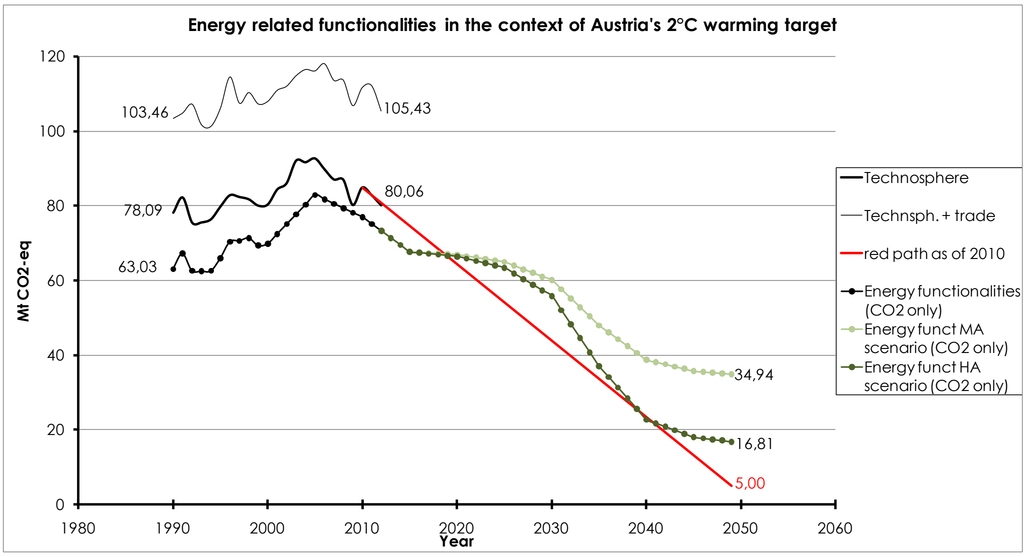
[1]) As on Fig. 7a but in per capita terms.

3.3 National emissions reductions scenarios assessment via the ETU framework

The ETU framework provides means of assessing the compatibility of any given national emissions reductions scenario with an assumed global warming target. As it enables us to translate the warming target into a budget of cumulative emissions, we can easily compare cumulative emissions resulting from the analysed emissions scenario against this budget. If the budget of cumulative emissions is exceeded the scenario does not comply with an assumed warming target.

While this method is particularly suited for analysing the evolution of a complete picture of future national GHG emissions, it can also be used to assess the feasibility of scenarios of emissions reductions of selected GHGs resulting from a specified set of functionalities with respect to an allowed national budget of total cumulative GHG emissions. For example we may apprise compatibility of an emissions scenario resulting from energy related functionalities (cf. chapter 4.1 of the research plan) with a warming target of 2°C in the following way: 1) We calculate cumulative GHG emissions for the analysed scenario (which in the case of activities related to the energy generation are virtually equal to the CO_2 emissions), and 2) We compare these cumulative emissions with a fraction of the national emissions budget that we allot to the considered set of functionalities (e.g. 70% of national emissions budget for energy related functionalities with 30% left for other functionalities). See Figure 8 and Appendix B.3 for further details.

Figure 8 Assessment of scenarios of CO_2 emissions resulting from energy related functionalities[1])



[1]) Two scenarios of CO_2 emissions resulting from energy related functionalities compared against a linear GHG emissions target path corresponding to 2°C warming target. The moderately ambitious (MA) scenario results in cumulative emissions of 2,210 Mt CO_2 in period 2010 – 2050, while the highly ambitious (HA) scenario anticipates cumulative emissions of 1,919 Mt CO_2. Neither of these scenarios is in line with 2°C warming as they exceed Austria's GHG emissions budget of 1,807 Mt CO_2-eq allowed for period 2010 – 2050 in this case. For a description of MA and HA scenario see Appendix B.

3.4 Directions for future research

We foresee two major directions for further research, which can be pursued in parallel and independently.

3.4.1 Towards functionality-based GHG inventories

Modelling techniques based on the functionalities approach are being developed to support identification of the most feasible solutions and policies aiming at a transformation of the current economy into a low carbon one. To this end, functionalities serve best if considered in interaction, not separately. The same is true for scenarios of GHG emissions resulting from future evolution of different functionalities: they can be assessed best if considered together, forming a complete picture of future emissions.

Being complete in assigning all national GHG emissions to functionalities, yet avoiding double-counting, is of utmost importance if a functionalities-based modelling approach is to be relevant for formulating GHG emissions reductions strategies. Therefore the development of a functionality-based analogue of sectoral emissions accounting currently in use is a key task for further research. Among other issues, it will require:

- Finding a one-to-one mapping (i.e. complete and avoiding double-counting) of sectoral inventories into a set of relevant functionalities covering all national GHG emissions (cf. sections 5.1 and 5.2)
- Addressing the issue of emissions embodied in international trade and consumption of goods produced outside of the Austrian territory and vice versa (net balance of imported and exported products and services)
- Development of data collection methods which will support the construction of the functionality-based emissions inventories in the future (e.g. collecting data on lifecycle emissions of stocks)

3.4.2 Exploring criteria of allotting national emissions budgets

Principles guiding the assignment of fractions of the global GHG emissions budget to specific nations are a matter not only of science, but also of international politics. The principle of equity of per capita emissions in 2050 used currently by the ETU framework has its scientific merits (cf. section 3.2). However, it also has disadvantages of a practical and political nature, namely:

- Achieving strict global per capita emissions equity in 2050 corresponding to any acceptable warming target (e.g. 2°C) imposes extremely stringent reduction demands for highly developed countries like Austria, while some developing countries would still increase their emissions. Such a course of action may be impossible for political, economic or technical reasons.
- Equity in per capita emissions does not take into account geographical inhomogeneity in the amount of GHG emissions required to support living of an individual at a certain

location (due to e.g. energy demanded to facilitate basic functionalities, or feasibility of employment of certain technologies in that location).

- Considerations of environmental justice may also be relevant.

There is a need for other criteria for the distribution of the global GHG emissions budget among nations which address the abovementioned issues.

4 Tier 1: The physical layer of a deepened structural modelling approach

4.1 Functionality focused modelling of energy related emissions

As elaborated in chapter 2, there is a need to come up with more relevant measures of economic activity. We suggest as an operational approach the use of wellbeing-relevant functionalities. This opens new perspectives for our understanding of the energy system.

In this context there is an emerging insight that for energy related activities the interaction of energy flows and the corresponding capital stocks which together provide the desired functionalities is most relevant. Another essential element for understanding energy systems is their cascade structure by considering explicitly the sequence of energy related functionalities, and the flows of useful, final and primary energy.

The physical structure (Tier 1) of an energy system as discussed in this section needs then to be embedded into the economic and institutional tiers of a comprehensive modelling framework.

- The first issue concerns measuring economic activity (typically a consumption or investment flow) or energy flows (frequently final consumption or primary energy supply).
- The second issue concerns the impact of changes in behaviour (e.g. changing lifestyles) and technologies (e.g. zero- and plus-energy standards in buildings).

4.1.1 Functionalities in a deepened structural model of the energy system

Following the mindset for a deepened understanding of our economies as discussed in chapter 2, functionalities are also at the core of a deepened structural model of the energy system.

An operational approach to energy related functionalities is classifying them according to the energy services they are providing:

- energy related functionalities for providing thermal services (at low or high temperatures),
- energy related functionalities for providing mechanical services (stationary engines and mobile engines for transport), and
- energy related functionalities for providing specific electrical services as lighting, electronics and for electro-chemical processes.

These functionalities are closely related to the energy cascade that represents the internal structure of an energy system, i.e. a sequence starting with energy related functionalities. Together with the relevant technologies, the demand for energy related functionalities determines the following energy flows:

- useful energy flows,
- final energy flows, and

- primary energy flows.

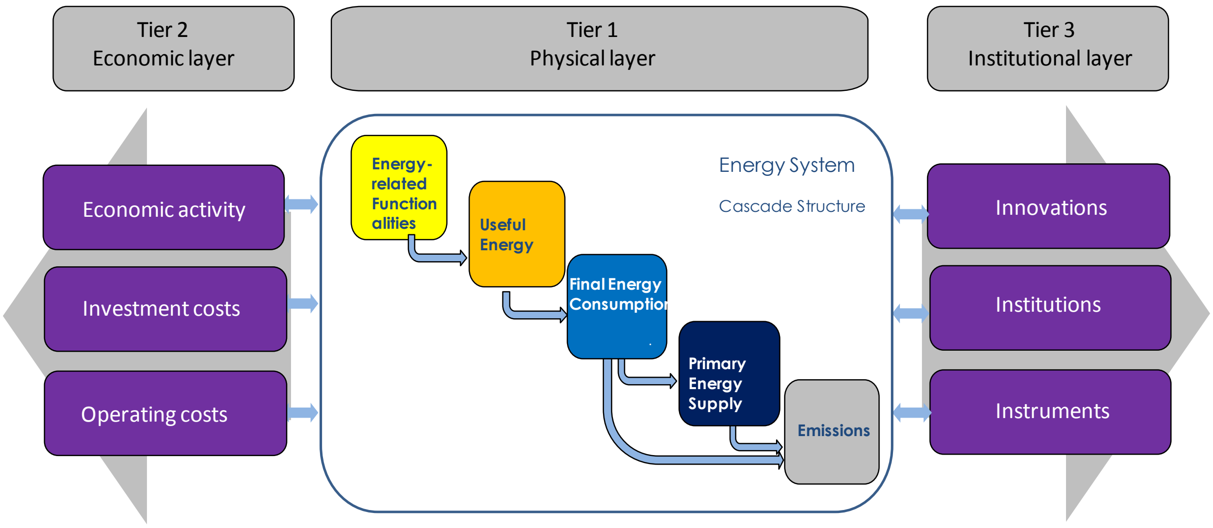
In a deepened structural model of the energy system therefore on each level of the energy cascade the relevant technologies for application, transformation and primary energy supply need to be identified.

4.1.2 Outline for a deepened structural energy model module

For analysing radical transformations which are necessary to achieve the goal of decarbonising the energy system a deeper understanding of the internal structures of systems is needed. A constituting feature of the internal relationships in an energy system is a layer of cascades, starting from energy related functionalities which we name synonymously energy services. We move on via useful and final energy consumption to primary energy flows. We denote this view of an energy system the "Cascade Structure" approach as illustrated in Figure 9.

This perspective of the energy system is fundamentally different from the mainstream focus on energy flows which neglects energy services relevant for wellbeing. Another distinguishing feature for the proposed deepened understanding is the inversion of the sequence of argumentation. Starting point are the energy services and by explicitly considering relevant application and transformation technologies subsequently the energy flows are determined at the respective levels of the energy cascade.

Figure 9 The "Cascade Structure" approach



The energy system and the resulting energy related emissions are embedded into the structures of an economy with a number of links between the physical, the economic and the institutional layers. Buildings, for example, interact with energy flows which are determined by the quality of the building stock, by user behaviour and the related incentives provided by costs (in Tier 2, the economic layer) and the institutional setting like building codes or economic instruments (in Tier 3, the institutional layer) as drivers for long-run structural change.

The cascade structure of the energy system

Looking into the internal structures of energy systems we distinguish a cascade of four layers as seen from Figure 10.

The top layer represents different types of energy related functionalities which are synonyms for the term energy services:

- thermal energy services for e.g. maintaining buildings at comfortable temperatures and enabling heat-related production processes,
- mechanical energy services for providing mobile or stationary services in all kinds of machinery, and
- specific electric energy services needed for electric motors, lighting and electronics.

Energy services are provided by useful energy which is characterised by its purpose as

- thermal applications in low and high temperature processes,
- mechanical applications in stationary and mobile engines, and
- specific electric applications as in lighting and electronics.

The next layer of the energy system is composed of the energy flows that are metered in households and companies and which comprises final energy consumption for

- heating and cooling in buildings and production,
- fuels for stationary and mobile engines, and
- electricity for machinery, lighting, electronics and electro-chemical processes.

The amount of final energy is determined by the amount of energy services desired on the one hand and the quality and efficiency of the corresponding application and transformation technologies on the other hand. In the context of application technologies, aspects of technologies particularly relevant for the transition to low energy and low carbon structures include the thermal quality of buildings, the efficiency of stationary and mobile engines or the efficiency of lighting and electronic devices. In the context of transformation technologies, heating and cooling systems and the conversion of primary energy into final energy as electricity and heat or the conversion of crude oil into fuels need to be considered.

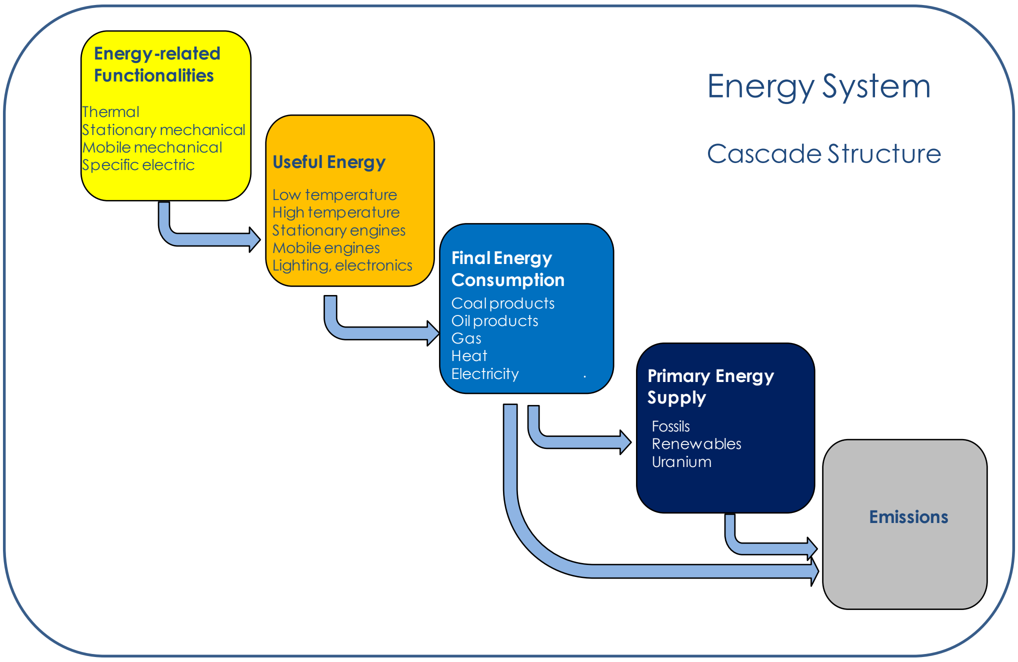
The lowest layer of the energy system concerns the primary energy flows as

- fossil energy (coal, crude oil, natural gas, fossil waste),
- renewable energy sources (thermal solar, PV, ambient and geothermal heat, wind, hydro, biomass), and
- uranium for nuclear transformation processes[10].

[10] For Austria relevant in the form of imported electricity.

Emissions from the energy system arise from fossil energy flows via transformation processes, including distribution losses, and final consumption of fossil energy sources. For understanding emission reduction potentials and emission reduction policies it is essential to identify these origins of emissions.

Figure 10 Layers of the cascade of an energy system



4.1.3 The analytical framework for a deepened structural modelling of the energy system

Based on the above described conceptual framework we develop the building blocks of an analytical model and exemplarily apply it to the energy balance data for Austria (see chapter 7).

This is complemented by a pilot model that is available on the ClimTrans2050 web platform. The pilot model provides an easy access both to the relevant data of the energy system and to user controlled interventions on key parameters. Users may change parameters, like the desired amount of supportive functionalities, the energy productivities in application and transformation or the energy mix. Mention should be made, however, that for each of these changes reasonable underlying storylines for implementation need to be provided.

In the following the essential analytical building blocks of the above motivated deepened structural model of an energy system are presented. Essential features in this modelling framework are

- the cascade of the energy system,

- the accompanying key variables which describe the sequence from energy services to transformed and primary energy flows, and
- the parameters which link these variables.

Definitions

The elements that a deepened structural energy model comprises are listed in the following.

Variables

S	energy related functionalities (energy services)
U	useful energy
F	final energy consumption
E	primary energy supply for domestic use
L	losses (in transformation and distribution)
C	CO_2 emissions

Parameters

T	transformation and application technology parameters (T_{SU}=S/U, T_{UF}=U/F, T_{FE}=F/E)
A	emissions parameters

Types of functionalities

hl	low temperature heat
hh	high temperature heat
es	stationary engines
em	mobile engines
le	specific electric functionalities for lighting and electronics

Types of energy flows

to	total
co	coal
oi	oil
ga	gas
re	renewables
el	electricity
ht	heat

Model structure for the energy system

Energy related functionalities (energy services)

At the top of the cascade, energy services S result from useful energy U via the energy productivity parameter T_{SU} which reflects the productivity of application technologies, e.g. the amount of useful energy needed for providing a unit of thermal service depends on the thermal quality of a building):

$$S = T_{SU} \cdot U$$

Useful energy

Useful energy U is obtained from final energy F via the energy productivity parameter T_{UF} which characterises the productivity and type of application and transformation technologies (e.g. the heating system of a building which transforms e.g. gas to heat):

$$U = T_{UF} \quad F$$

Final energy

Final energy F is the outcome of transformation processes applied to energy supply E via the transformation parameter T_{FE} (e.g. a cogeneration unit which transforms primary energy into final energy):

$$F = T_{FE} \quad E$$

Primary energy

Finally the decision about the composition of the primary energy mix needs to be made which refers to the elements of primary energy E.

Losses

The energy flows between the layers of the energy cascade are exposed to losses which result from transformation and distribution.

Summarising these relationships we realize the essential inputs that determine the amount of available energy services:

$$S = T_{SU} \quad T_{UF} \quad T_{FE} \quad E$$

On the layers of the cascade of the energy system relevant decisions about the choice of technologies have to be made, namely the application technologies for services and useful energy and the choice of transformations for the energy supply. Furthermore in all transformations and applications there is a choice of the energy mix.

Emissions

At two stages of the energy cascade we can monitor CO_2 emissions C.

Emissions from energy transformations C_E originate from energy inputs E via emissions parameters A_{CE}:

$$C_E = A_{CE} \quad E$$

Similarly emissions from final energy use C_F result from final energy F via emissions parameters A_{CF}:

$$C_F = A_{CF} \ F$$

These emissions parameters are specific for each type of fossil energy.

4.1.4 Next research steps

Deepening the functionality approach to energy modelling

- Developing operational indicators for energy related functionalities: Supporting information for obtaining a better understanding of thermal, mechanical and specific electric services.
- Identifying gaps in currently available databases and developing proposals for improving data collection activities: Currently available databases are not adequate for deepened structural modelling and need to be extended with respect to the concept of functionalities.
- Designing model modules for specific energy related functionalities: Tackling the complexities of specific functionalities, as in the case of shelter the role of temperature, lighting, and communication facilities.
- Collecting a knowledge base about technologies which are in particular relevant for the transition to low energy and low carbon structures: Whenever new technologies emerge, they can be evaluated with respect to energy productivity, energy sources and emissions along the cascade structure of the modelling approach. It is expected that energy systems will experience not before long a number of breakthrough technologies, ranging from a new generation of batteries to new options for distributed generation technologies.

Modelling the linkage between Tier 1 and 2

1. Providing the details on technologies and investments.
2. Modelling the impacts of these investments on energy productivity and energy demand and operating costs.
3. Modelling the impact of these investments on other sectors of the economy including energy demand and related emissions.

Modelling the impact of Tier 3 on Tier 1

6 Evaluating the relevance of the institutional layer e.g. economic instruments (taxes, subsidies), prices and income and income distribution, command and control regulations (standards, zoning regulations) for energy related decisions.

7 Capture the transmission process from drivers for innovative technologies and business models that impact the energy system.

4.2 Non-energy related emissions

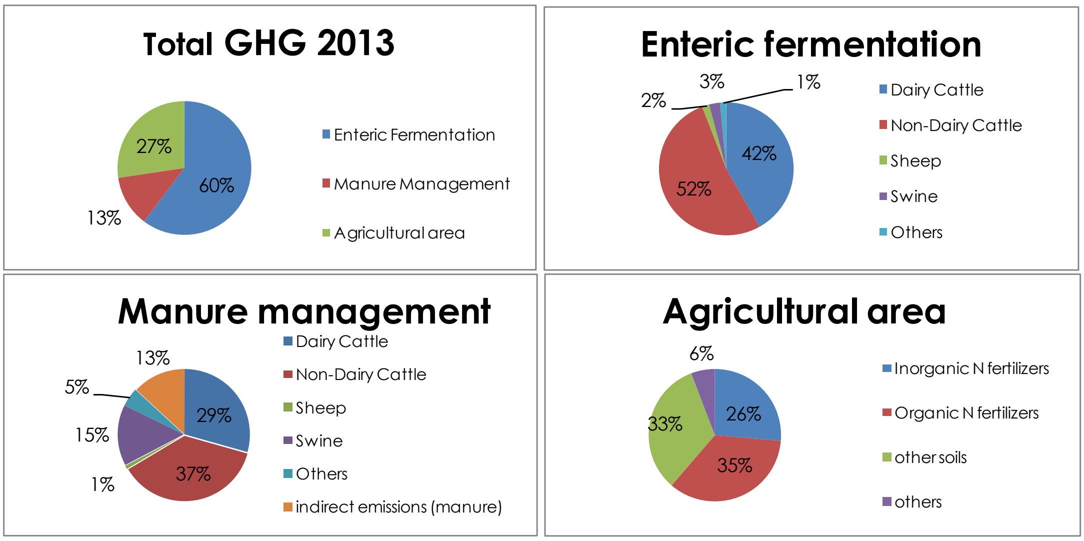
As has been elaborated in chapter 2 the concept of functionalities leads to a new understanding in the generation of emissions. Non-energy related emissions arise from industrial production (e.g. iron and steel industry, cement industry), agriculture (enteric fermentation, manure management and application of fertilizers) and to a minor extent from the extraction and distribution of fossil fuels. Land use, land use change and forestry (LULUCF) can either be a source or sink of emissions. Furthermore non-energy related GHG-emissions arise from waste disposal and the use of F-gases. Generally speaking emissions from industry are associated with the production of reproducibles, while emissions from agricultural production and waste disposal (of organic material) are associated with the functionality nutrition. In the following subchapters we focus on the functionality nutrition[11].

4.2.1 GHG Emission Inventory

The national GHG emission inventory (UBA, 2015b) displays industrial process emissions calculated according to the IPCC manual: Specific emission factors reflecting the applied technology are multiplied by the related activity, such as production of steel, cement, lime or ammonia.
The calculation of emissions from agriculture is based on the estimation of the livestock of each animal type, the associated amount of enteric fermentation and manure generated and the amount of fertilizers applied per hectare of agricultural soil. Main emission sources of the sector agriculture according to the Austrian GHG emission inventory are non-dairy and dairy cattle and the use of fertilizers (Figure 11). Emissions of the sector agriculture differ from the emissions related to the functionality nutrition: Part of the agricultural production is not used for food production but e.g. as raw material for bio-based industry or for energetic use. Likewise, production of food can cause emissions outside the agricultural sector (e.g. fertilizer production, transport, emissions from food waste, ...).

[11] For a comprehensive open source model reflecting the Austrian GHG emission inventory a special focus needs to be given to modelling process emission in the supply of reproducibles for functionalities.

Figure 11 Emissions from agriculture in the national inventory in Austria in 2013.



S: Umweltbundesamt, 2015a.

4.2.2 Functionalities in a deepened structural model of non-energy related emissions

Like for the energy related emissions, functionalities are at the core of a deepened structural model of non-energy related emissions. The common approach of modelling industrial and agricultural process emissions focuses on the production process (the supply side) but does not explicitly consider the demand side (in the context of ClimTrans2050 the functionality).
The functionalities approach starts at the other end of the food cascade (Figure 12). The intuition is that a transformation process starting at the demand side discloses more options for emission reductions than one starting at the supply side. Therefore this approach explores the demand side and its drivers. Better knowledge on the demand drivers allows more targeted policies to induce a demand shift. Nutrition might change over time in terms of amount and composition. For example, the amount of calories taken in per day and capita may change over time. More importantly, the composition of consumed calories (e.g. the shares of meat, vegetables etc.) and the shares of proteins, fat and carbohydrates will change (e.g. as a result of habits, lifestyles, but also influenced by future findings in medicine). Thus the primary goal of the functionality approach is to analyse the demand and its driving factors and how these can be influenced to achieve a targeted reduction of emissions. The next step is to assess which types of food are most relevant for consumption. Finally it is assessed how the food can be produced with as few emissions as possible (Figure 12) "Food needed" denotes the amount of calories humans require for everyday activities. Optionally the amount of food required for pets can also be included in this category. The amount of "food needed"[12] may be used as quality control for the model output, since it provides a

[12] This could e.g. be based on recommendations of the WHO.

lower boundary (otherwise people would starve). "Food consumed" is usually a higher amount than "food needed" because of preferences, sports activities, intolerances, malnutrition, bulimia or overweight, etc.. Likewise, the amount of "food bought" is higher than the amount of "food consumed", due to losses in cooking and waste (intentionally and unintentionally[13]). Finally, not all food is sold but is disposed to waste in wholesale and retail (shops and markets) or food service (restaurants, hotels, takeaways). Furthermore there are losses in food production (agriculture) and processing (food industry). "Food supplied" will hence be larger than "food bought".

A Swedish study (IVL, 2016) reports that total food waste in the EU-28 amounted to 87.6 million tons in the year 2012, which corresponds to 173 kg per person and year or roughly half a kilogram per day and capita. 11% of the losses occur in primary production, 19% in processing, 5% in wholesale and retail, 12% in food service and the largest share with 53% in households. That means a quarter of a kilogram food waste per capita and day is generated directly in an average EU-household.

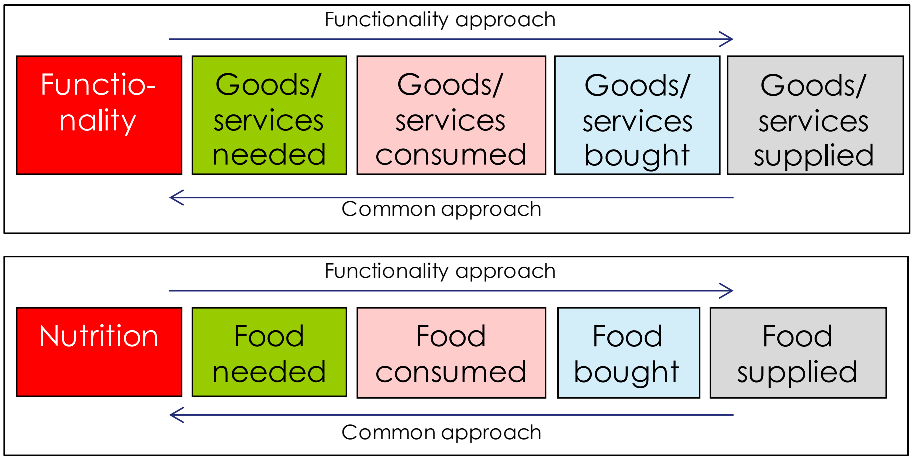
Figure 12 is an analogy to the energy cascade (Figure 10). It shows the common modelling approach starting from the supply side and the functionality approach, starting from the demand side. Food, represented by calories, can be considered as a special form of energy. However, food also needs to provide micronutrients such as vitamins, minerals and trace metals.

In the context of functionalities non-energy related emissions will arise from the functionality nutrition and from reproducibles (e.g. production of goods).

Starting from food as consumed good a generalized cascade structure can be deduced for each good (reproducible) or service (e.g. health, administration). This cascade is also depicted in Figure 12. Figure 13 shows how this general good and service cascade is embedded in the three-tier approach including emissions (Figure 13). It also shows the interaction and interdependency between the three tiers, which will be further elaborated in chapter 6. While emissions are modelled in Tier 1, it is important to understand the economic implications (Tier 2) and the institutional setting (Tier 3) shaping the physical layer (Tier 1).

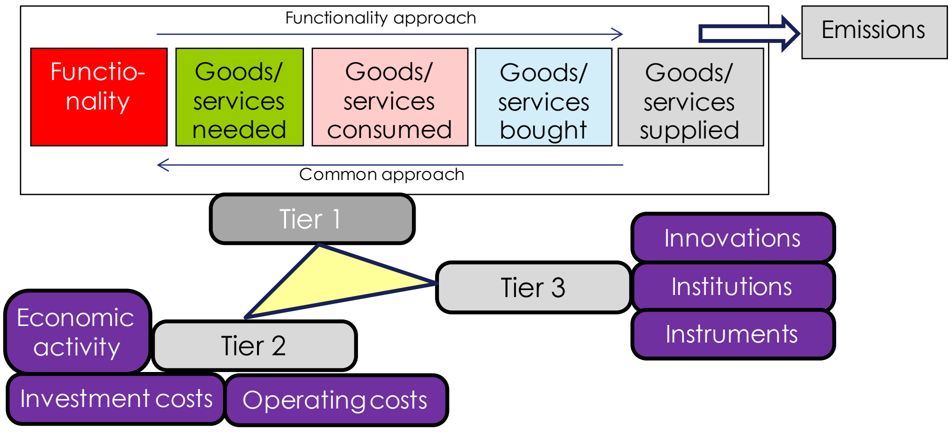
[13] Intentional losses in cooking arise e.g. from peelings or bones; intentional waste are leftovers (including food that is not eaten, because it does not taste well); unintentional losses are e.g. mishaps in cooking and rotten food.

Figure 12   Food cascade and goods/ services cascade in analogy to the energy cascade[1])



[1]) Imports and exports have to be considered in "goods/ services bought" or specifically "food bought"

Figure 13   The "cascade structure" for non-energy purposes in the context of the three-tier approach

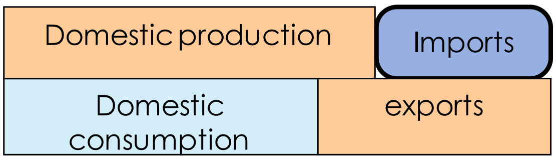


In order to understand the food cascade more precisely, Figure 14 to Figure 16 provide a more detailed insight into the structure of the food cascade. Figure 14 shows how imports and exports are represented. In the current inventory system emissions are solely calculated from domestic production (including exports) and imports are not taken into account. This is very feasible for balancing purposes, since it guarantees that neither emissions are overlooked nor double counted, but not from a consumption perspective. From a global environmental perspective, the geographical origin of emissions is not relevant. From a national environmental perspective also embedded emissions from imported food should be addressed. This argument not only holds true for food products but any imported goods.

Figure 14 provides a more detailed insight into the structure of the food cascade. Figure 14 shows how imports and exports are represented. In the current inventory system emissions are solely calculated from domestic production (including exports) and imports are not taken into account. This is very feasible for balancing purposes, since it guarantees that neither emissions are overlooked nor double counted, but not from a consumption perspective. From a global environmental perspective, the geographical origin of emissions is not relevant. From a national environmental perspective also embedded emissions from imported food should be addressed. This argument not only holds true for food products but any imported goods. Besides that also from an economic perspective, it is questionable whether to import all food to Austria would be an option.

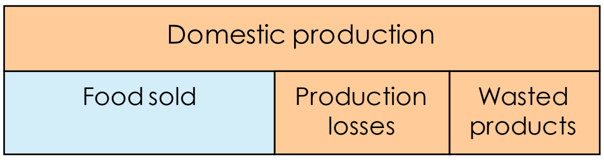
Figure 14 shows that there is an equality of imports and domestic production versus exports and domestic consumption. The shares of production and imports will usually be different for each product, as well as the shares of consumption and exports. For some products imports will be 0% (e.g. tap water), for others 100% (e.g. bananas).

Figure 14 Balance of domestic production and consumption including imports and exports



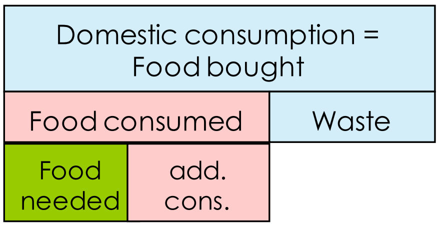
Domestic production is further broken down in Figure 15. Consumption can be considered as the sum of food sold (to households, food services, shops and markets within Austria and abroad; i.e. including exports), production losses (agricultural and industrial production, e.g. from grain to bread) and wasted products (not sold by the primary producer, e.g. fruit and vegetables that do not fulfil quality requirements). Note that "food sold" in this figure is different from "food bought" in the next figure.

Figure 15 Specification of domestic production



"Food bought" in our understanding equals domestic consumption. Figure 16 shows a disaggregation of domestic consumption (i.e. food bought in Austria regardless whether it has been produced in Austria or imported) into food and beverages actually consumed (eaten or drunk) and food that is wasted (either rot or cooking waste like skins, stones, leafs or crusts) or not sold in food service, shops and markets. "Food consumed" is further disaggregated into food needed and additionally consumed food (e.g. overweight or food that cannot be converted into calories because of intolerances, allergies or illnesses). "Food needed" represents the minimum amount needed to avoid starving.

Figure 16 Specification of domestic consumption



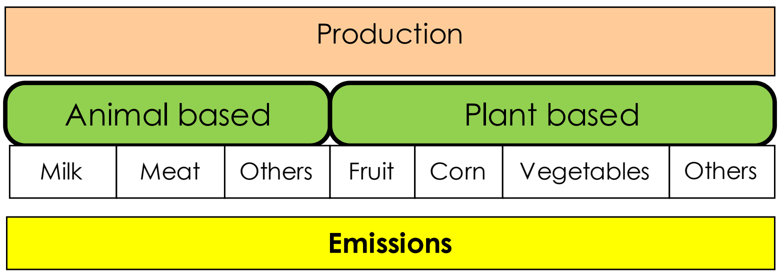
add. cons.: added consumption

For describing the functionality nutrition in Austria (as the main driver for food production), the following information is relevant:

1 population in Austria (including specific demographic parameters like age, sex and work),
2 amount of consumption of selected types of food per capita,
3 shares of domestic production, import and exports of the food types, and
4 llifestyles and social factors.

A model suitable for analysing transformation processes has to represent the food cascade and the economic and institutional interdependencies. One step is to select representative types of food for modelling nutrition purposes. The modelling structure needs to capture what amount of which products is needed to cover the functionality, as well as the energy input and the corresponding emissions for the individual production processes of each food type (Figure 17). Total emissions allocated to the functionality nutrition then result from the sum of all these production processes, depending on the system boundaries applied (e.g. distribution or cooling chain may also be assigned to this functionality[14]). Figure 17 suggests a categorisation of food types. Food is divided into animal based products like meat (including fish and insects), milk and others (e.g. eggs, gelatine, honey), and plant based products like fruit, corn (i.e. all sorts of grains), vegetables and algae and others (e.g. mushrooms). In all categories the derivatives of the main source are included, e.g. milk products (yogurt) in milk, fruit juice in fruit, bread in corn and sugar in vegetables.

Figure 17 Simplified breakdown of calorie production leading to emissions.



[14] In any case double counting of emissions needs to be avoided.

Overproduction (including export of goods) and losses in the production of reproducibles are strictly speaking part of different functionalities but can also be covered within nutrition. For emission inventories only the emissions from domestic production are covered.

Figure 18 depicts two examples (example 1: milk; example 2: fruit) to illustrate relevant stocks and flows that have to be taken into account for modelling the functionality nutrition. For the production of milk (and subsequent products like cheese) the most important stock is the number of dairy cows, sheep and goat providing milk. Pasture land for the animals is needed as well as building infrastructure (e.g. stables, fences). Furthermore milking machines and vehicles are part of the technical infrastructure. Important flows connected to milk production are fodder for the animals, provision of a healthy environment which includes medical services and dealing with manure generated by the animals, energy for machinery and buildings[15] as well as workforce for maintenance.

The production of fruit (example 2) has similarities to example 1 with respect to stocks except for the fruit growing plants (trees and bushes). Naturally the use of the area and buildings (e.g. silos) and the type of machines differ significantly from example 1. The most important additional flow is the use of fertilizers.

Figure 18 Examples for material stocks and flows related to the functionality nutrition

Example 1 Milk

Stocks	**Flows**
Animals	Fodder
Area	Medical services
Buildings	Waste
Machines	Manpower
	Energy
	Maintenance

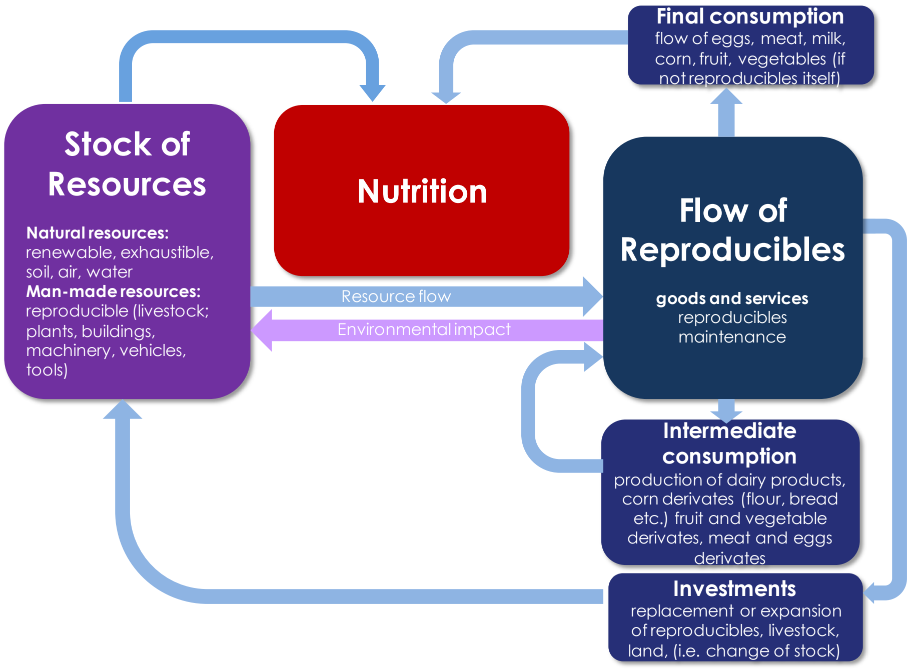
Example 2 Fruit

Stocks	**Flows**
Area	Rent
Buildings	Fertilizers
Machines	Waste
Plants	Manpower
	Energy
	Maintenance

Figure 19 illustrates the modelling structure for the functionality nutrition along the lines of the general deepened structural modelling approach in Figure 4 as described in chapter 2. Figure 19 depicts the relevant stocks and flows and their interactions for providing the functionality nutrition. As can be seen in the figure, the most important stocks are soil, area, air, water and reproducibles like livestock, plants, machines and buildings. Investments will increase the amount, improve the quality or maintain these stocks. Reproducibles make up the intermediate consumption (e.g. milk for the production of yoghurt) and are also needed for providing the final consumption of foods.

[15] Again double counting of emissions needs to be avoided.

Figure 19 A deepened structural modelling approach for emissions related to the functionality nutrition



4.2.3 Next research steps

The following next research steps cover nutrition related emissions; they do not yet cover the whole spectrum of non-energy emissions. Emissions from industrial processes, F-gases and waste disposals are related to the functionalities shelter and access to persons and goods; e.g. changing the quality of the building stock (refurbishment or new buildings) causes emissions (both from energy use and from processes) in e.g. iron and steel industry.

For land use, land use change and forestry a suitable functionality still has to be explored.

Research tasks for Tier 1 (nutrition)/ what the model should be capable of:

- The open source model should aim at providing the structure of the status quo starting from functionalities; the amount of total emissions should be in coherence with national inventory (at least for Austria overall).
- The availability, utility and quality of relevant data such as population growth, dietary habits (amount of consumed milk products, different types of meat, vegetables, …) has to be assessed.
- Gaps in currently available databases need to be identified and suggestions for improving data availability with respect to functionalities need to be made.
- Scenarios for future nutrition and how this consumption can be influenced (behavioural changes -> Tier 3) have to be developed. Factors of health and wellbeing should also

be considered, e.g. the calorie demand should not be covered only by a single source of food.

- The model module should be capable of analysing changes of technical parameters such as
    - production of calories per animal,
    - yield of grain with a certain content of calories/proteins/carbohydrates per hectare of land,
    - amount of fertiliser needed per hectare of land,
    - emission factors (e.g. race of cattle).
- An assessment of uncertainties concerning data and model results needs to be made; the focus should be on the most relevant and sensitive parameters.

Modelling the linkage between Tier 1 and 2

The open source model should

- interlink most important economic parameters for nutrition and related emissions,
- take into account the structure of the agricultural sector (size of farms, percentage of organic farming,…),
- interlink technical parameters (e.g. learning curves, but also complete switches of technologies) and emissions,
- allow for and integrate breakthrough technologies,
- change technological coefficients over time,
- deal with boundaries and restrictions (e.g. area, water, human resources),
- avoid double counting of activities (reproducibles, infrastructure).

5 Tier 2: The economic layer of a deepened structural modelling approach

5.1 Functionalities in the context of economic activities

Human activity is driven by basic needs which can be captured by the concept of "functionalities". Basic functionalities include shelter, nutrition or the access to goods and people (mobility).

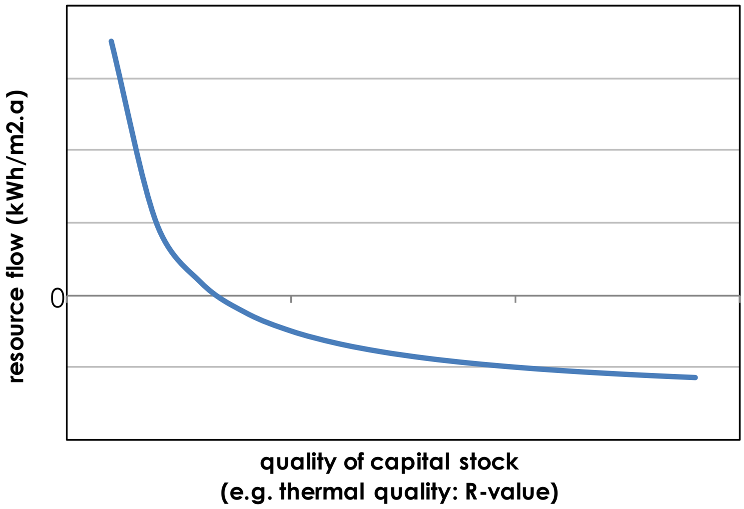
For a techno-economic evaluation of transition based on functionalities, proxies are needed for measurement and evaluation. The extent of the provision of a functionality is driven by demand which in turn is driven by demographics (population) and lifestyles (see chapter 6 for a discussion).

A functionality can be served by a multitude of different technologies (characterised by different degrees of resource productivity), which determines economic activities. The economic analysis allows comparing the resources required to serve functionalities, and thus identify the most resource-efficient pathways. In economic terms this translates into different investment and operating costs as well as different sectoral demand structures.

For the economic evaluation of functionalities the interaction of stocks and flows is crucial (see chapter 2 for a broader discussion on the importance of stock and flow interaction). We thus suggest to apply the concept of user costs, since it captures both stock related costs (i.e. capital costs) as well as costs attributed to flows (i.e. operating costs). Annual user costs are the sum of annualised capital costs and annual operating costs and (at least should be) an important determinant for individual decision making. While the differentiation between those two subcategories of costs is crucial, usually they are interdependent, e.g. since in most cases the quality of the capital stock determines the level of operating costs.

Hence, users face a situation where they can choose between either having low capital costs (in that respect a thus measured lower quality of the stock) and a high resource flow with high operating costs or vice versa (i.e. a high quality capital stock with low operating costs). These cost considerations build upon the physical relationship as depicted in Tier 1 (the physical layer) which here serves as the connecting point to the economic analysis. It is depicted in Figure 20 for the example of the functionality shelter. Each combination of these two cost components (single points on the isoline in Figure 20) reflects a certain technology, with a distinct energy intensity.

Figure 20 Relationship between resource flow and capital stock quality for the example of shelter.



Since often GHG or CO_2 emissions are connected stronger to annual flows than to the creation of the stock itself, a transition to a low carbon economy could be achieved by increasing the quality of the stock, to decrease the necessary annual flows and thus emissions.

For an economic evaluation, building upon the relationship depicted in Figure 20, we require the respective annualised costs of improving the stock (new technology) and the resulting resource and cost savings. Both should be given normalised to the unit applied.

Thus, for the transition analysis to a low carbon economy not only the description of the current state of technologies is necessary, but also cost profiles of new technologies, including potential breakthrough technologies which may substitute dominant current technologies. Note that the functionalities per se do not change within this transition, only technologies to serve them and lifestyles to draw on them do. Hence for each functionality new (high-potential) technologies or fundamental behavioural change need to be identified and respective cost information needs to be gathered. The possible shifts from the set of currently used technologies (and the associated costs) to a set of new (breakthrough) technologies or behavioural patterns describe available transition processes. Both technologies and behavioural patterns affect economic structures.

While the perspective of the user is crucial for incentives (Tier 3) to actually achieve transition, implications of such a transition have aggregate effects beyond those on the respective individual user. This aggregate level thus is the second crucial one to be in the focus of analysis and consideration. In economic terms it is the macroeconomic perspective (i.e. capturing the macroeconomic effects of the transition) that is at the core of our interest at this level. Macroeconomic effects emerge via the interlinkages across different economic sectors and agents. For example, if there is increased demand for construction activities for the thermal improvement of the building stock, this generates increased demand for labour and other intermediate inputs in sectors that provide products which are needed for construction activities (e.g. insulation material, transport etc…). Also foreign trade may be affected by the transition if import intensities of products and technologies for transition options differ from those of conventional technology options. For example, if insulation material for buildings is over(under)proportionally imported, the foreign trade balance worsens (improves). Any acceleration of the diffusion of transition technologies is reflected in stronger macroeconomic effects. To reveal these overall economic effects input-output based analysis may be applied, since this method captures the interrelationships between all economic sectors within a macroeconomic consistent framework.

5.2 Connecting the physical and the economic layer of transformation processes

This section gives a formal overview of the connection between the physical and the economic layer of transition analysis.

Variables

S	functionality
R	resource demand
U	useful energy
e_S	resource intensity of a functionality
d_S	resource productivity of a functionality
v	improvement of resource intensity
i(v)	function between investment and resource intensity improvement
g	annuity factor
r	interest rate
t	financing period
n	annual unit user costs for financing of stock improvement
p	resource price
B	scaling parameter
h	net cost savings per unit
H	total cost savings
V	resource cost savings
INV	total investment cost
X	gross production output
a	fixed proportion coefficient in production
Y	final demand

In order to emphasise the connection between Tier 1 and Tier 2, we start with an overview on the relevant parts of Tier 1 (efficiency and productivity changes), which is then linked to the analytical structure of the economic analysis at Tier 2.

The user cost perspective

To serve a given functionality (S), certain resources (R)) are needed, hence the resource intensity of functionality S (e_S) is given by:

$$e_S = \frac{R}{S}$$

This expression already describes the current technology in terms of its resource intensity, or equivalently the quality of the current stock. Taking the inverse yields the current technology's resource productivity (d):

$$d_S = e_S{}^{-1} = \frac{S}{R}$$

Parameter d_S thus describes how much units of a functionality can be provided per unit of resource input. R may be replaced for some functionalities by useful energy (U) which would results in energy intensity (U/S) and energy productivity (S/U); the connecting parameter to Tier 1 and the energy related emissions.

When aiming for a changed stock with higher quality (in Figure 22: moving to the right along the horizontal axis), we are interested in the improvement of resource intensity (in Figure 22 moving downwards along the vertical axis), which is described by:

$$v = \frac{\Delta R}{S}$$

This improvement gives the transition in terms of energy intensity. The respective change in energy productivity can be directly fed into Tier 1 and is given by:

$$\frac{\Delta S}{R} = \left(\frac{R}{S} + \frac{\Delta R}{S}\right)^{-1} - \frac{S}{R}$$

The improvement in resource intensity (v) not only drives resource demand but also the investment requirements connected to the improvement of the stock's quality. Let function i(v) describe this relationship between investment and resource intensity improvement per S.

As we are interested in the annual user costs, i(v) needs to be annualised using annuity factor g, depending on the assumed interest rate r and financing period t:

$$g(r,t) = \frac{(1+r)^t\, r}{(1+r)^t - 1}$$

The annual unit user costs (n) for changing the technology (or increasing the stock's quality) are thus given by:

$$n = g(r,t)\; i(v)$$

The net cost savings per unit (h) for the user are then calculated by the difference between the value of saved resources and the annualised user costs:

$$h = v\,p - n$$

with p being the resource price for one unit of the respective resource. If h is positive, the change in the stock's quality is economically reasonable from a user cost perspective.

In a final step, net unit cost and resource savings as well as investment requirements may be scaled up to the national level, using a scaling parameter B. Total cost savings are given by:

$$H = h\,B$$

total resource cost savings by:

$$V = v\,B$$

and total investment cost requirements by:

$$INV = i\,B$$

The macroeconomic perspective

In a next step we suggest a macroeconomic analysis in order to reveal the effects of the transition at the aggregate level, often of indirect nature. For a macroeconomic analysis, V and INV are at the center of interest, since V describes the change in final demand and INV describes the investment requirements for the transition. Note that the change in final demand affects the economy continuously (i.e. during the operating phase), whereas the investments are a one-time requirement (i.e. during the investment phase) to trigger the changes in final demand (see section 5 and Figure 21 for a specific example).

For the analysis of the macroeconomic effects of the transition we suggest an input output analysis as a core element, since this approach captures the interlinkages between sectors, but still keeps complexity and modelling effort manageable. The input output table for Austria is publicly available, which is a good basis for an open source modelling approach. The input output approach describes the economy balancing the supply and demand side.

$$X_i = \sum_j X_{ij} + Y_i$$

where X_i is gross output or total supply of sector i (i = 1,…,n), X_{ij} are the sales of good i to sector j and Y_i is final demand for good i. X_{ij}, which can be also interpreted as the needed input of i in the production of j, can be expressed as a constant share of j's total output:

$$X_{ij} = a_{ij}\,X_j$$

where a_{ij} describes as a fixed proportion coefficient how much of sector j's gross output is coming from input from sector i. Hence:

$$X_i = \sum_j a_{ij}\,X_j + Y_i$$

which gives a system of n linear equations in 2n variables (X_i and Y_i) and n^2 coefficients (a_{ij}). When specifying the demand levels Y_i, n unknowns are left (X_i) which can be solved using the n equations. Since the equations are linear, the model can be solved by matrix algebra.

Rewriting this model in matrix algebra gives

$$\mathbf{X} = \mathbf{AX} + \mathbf{Y}$$

where X is a nx1 vector of gross output, A is a square matrix of nxn (a_{ij}, describing intermediate input coefficients) and Y is a nx1 vector for final demand. Rearranging yields:

$$\mathbf{X} - \mathbf{AX} = \mathbf{Y}$$

I being an nxn identity matrix further rearrangement gives:

$$(\mathbf{I} - \mathbf{A})\mathbf{X} = \mathbf{Y}$$

and

$$\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{Y}$$

with $(I\text{-}A)^{-1}$ being the inverse of (I-A), also called the "Leontief inverse".

Investment needs (*INV*) and related changes in user costs (*V*) that are triggered by transformation options are the input to changes in final demand Y that translate into gross output effects of all economic sectors and corresponding labour market effects. Taking thermal refurbishment of buildings as one transformation option, we could think of a reduction in final demand of oil for heating, and an increase in final demand for construction services. The reduced demand for energy flows for heating materializes over the whole life time of buildings, whereas the increase in demand for construction services (i.e. investment phase) affects the economy only once. This approach may reveal feedback effects within the transition process. For example an increased demand for construction services may lead to more transport demand, which may generate additional emissions which would not have been captured without an environmentally oriented macroeconomic model.

What is crucial for the analysis of transformation options from a macroeconomic perspective is that for new technologies (but also fundamentally changed behavioural patterns) the fixed technical coefficient a_{ij} may change, since new technologies may translate into altered production processes (for e.g. buildings, or energy) with fundamentally different intermediate consumption structures. In this broader perspective, one needs to model technological change which is triggering macroeconomic effects.

For non-energy related functionalities (e.g. nutrition), emissions result from technological or bio-organic processes. When aiming at a reduction in emissions originating from these processes, strategies can be a reduction of the activity level of the process itself (e.g. by reducing demand), or by introducing new processes with lower emissions, substituting for the current ones. Using the functionality nutrition as example, one strategy may be to reduce meat consumption and increase vegetarian nutrition instead. This may lead to a change in resource intensity (R/S), resource productivity (S/R) and hence emissions.

Note that for each functionality this explorative approach might have to be adjusted for some functionality-specific characteristics, yet the overall approach is the same and can be summarised as follows:

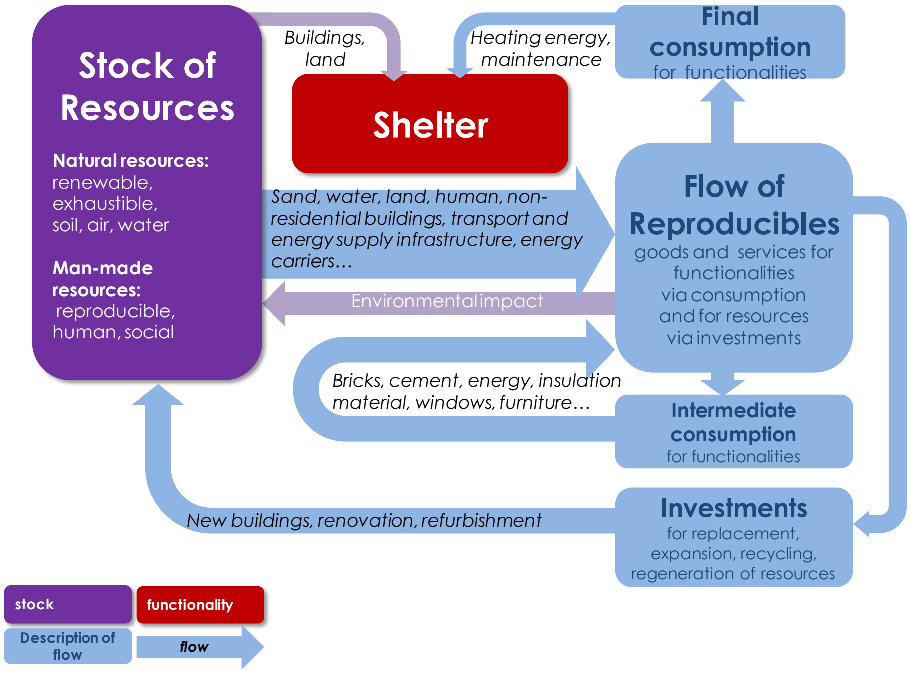
- Define functionalities and respective proxies
- Identify technologies serving these functionalities in the current state

- Identify new technologies with potential for substituting current technologies (including the extent of possible substitution)
- Derive cost of changing to new technologies
- Compare resource, emission and economic effects across technologies at both the user and aggregate socio-economic level.

5.3 Shelter as example for the application of the functionality approach

The deepened structural modelling approach, as developed in chapter 2, is illustrated for the functionality shelter in Figure 21. The figure explains the underlying stock flow interactions. Shelter results from a combination of a certain quality of the building stock and a flow of resources (e.g. energy flows for heating and other material flows for maintenance). To serve the functionality shelter complex interactions of stocks and flows occur. For the production of buildings resources such as sand, water, land and human resources are needed, which trigger demand for intermediate goods such as bricks, cement or energy. The production of these intermediate inputs also requires resources. In Figure 21 it is indicated that via investments in buildings (or in a changed quality of the building stock) components are added to the stock of resources. This stock in combination with the consumption of e.g. energy flows for heating provides the functionality shelter. The supply of heating energy itself results from a combination of different inputs such as energy supply infrastructure, energy sources and human resources. For the economic evaluation, the described complexity has to be transferred into inputs for the input-output analysis.

Figure 21 Stock-Flow interaction for the example of functionality Shelter



For the economic evaluation of the example Table 2 shows five steps that need to be transferred into economic relevant terms.

Table 2 Shelter as example for applying the functionality approach via refurbishment

General task	Description of task for the example of shelter	
1) Definition of functionality and respective proxy	1 m^2 of residential area kept at constant temperature	S
2) Description of current technologies serving the functionality in the current state	current stock with a certain heating energy demand in kWh/m^2	U/S S/U
3) Description of technologies with potential for substituting current technologies	refurbishment; energy heating demand improvements per m^2	$v = \Delta U/S$
4) Description of cost of changing to new technologies	costs per m^2 for improving heating energy efficiency by m^2	i(v)
5) Comparison of energetic and economic effects across technologies	compare energy and cost savings with investment requirements, relative to a system with no improvement	v, h, i V, H, INV

5.3.1 Definition of functionality and respective proxy

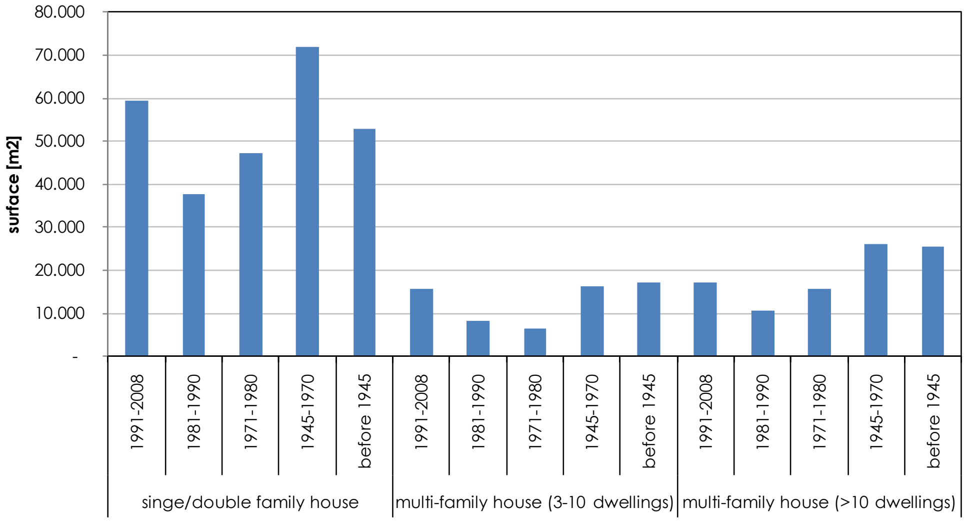
Taking shelter as an example, we use 'm^2 of residential area which is held at a constant temperature' as proxy to measure the functionality. The different technologies which serve the functionality shelter are represented by different classes of thermal quality of buildings (measured by heating energy demand in kWh/m^2).

5.3.2 Current technologies serving the functionality in the current state

The current stock at stake is the residential building stock and the associated costs are annual financing costs for availability of these buildings, whereas the corresponding flow is annual heating energy demand with the associated operating costs of annual expenditure for heating energy.

The currently used technology is described in Figure 22 to Figure 24. Figure 22 shows the residential building stock in m^2 of residential surface for different building types and building periods. 63% of the surface is attributed to single/double family houses (SDFH), whereas 15% to multi-family houses with 3-10 dwellings (MFH3-10) and 22% to multi-family houses with more than 10 dwellings (MFH>10). Within the type SDFH, the building period 1945-1970 has the largest share (17% of total; ~72,000 m^2).

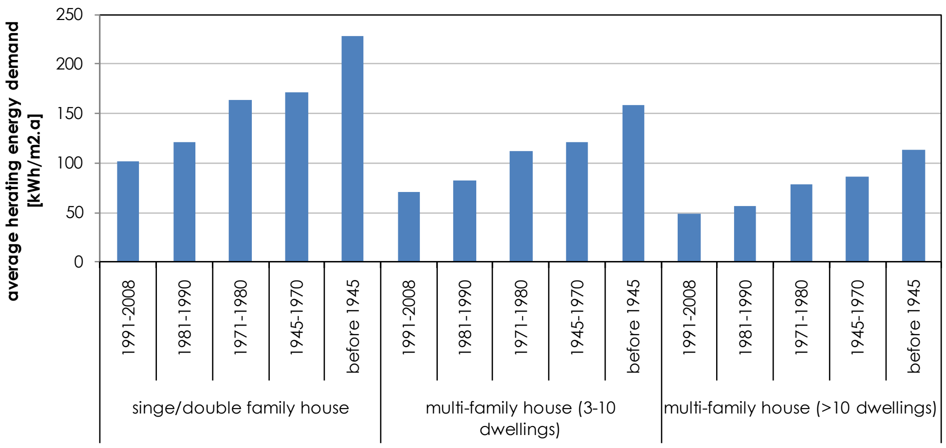
Figure 22 Current residential building stock in m² of residential surface for different building types and building periods



S: based on Müller, 2015.

Figure 23 gives average annual heating energy demand (U/S) for the different building types and periods in kWh/m². Within every building type, newer buildings show lower energy demand per m². SDFH show the highest energy demand (159 kWh/m² on average), followed by MFH3-10 (113 kWh/m²) and MFH>10 (93 kWh/m²). We see that buildings with a higher density of residential area or dwellings have a much lower energy demand.

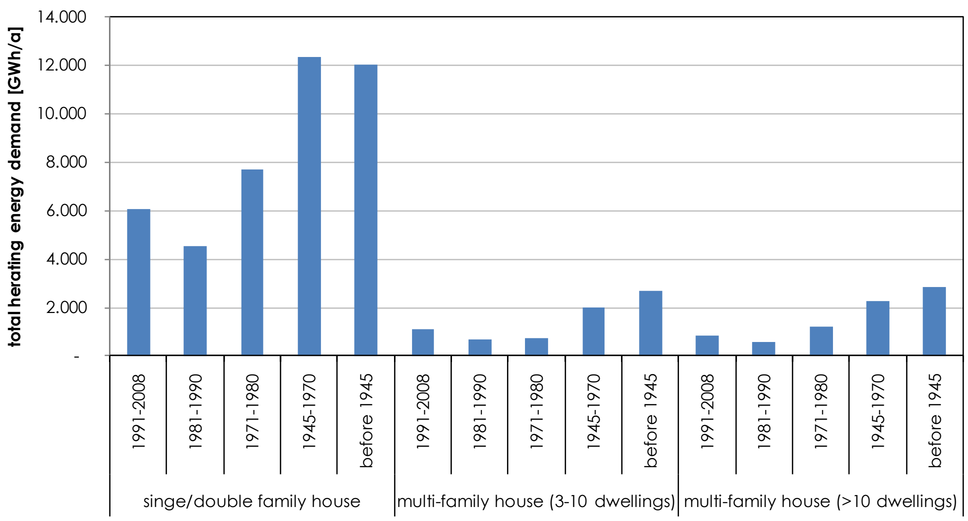
Figure 23 Average annual heating energy demand for the different building types and construction periods in kWh/m²



S: based on Müller, 2015.

When multiplying total residential surface (m^2) and energy intensity (kWh/m^2), this yields total heating energy demand, which is given in Figure 24. In total, Austria's heating energy demand for residential buildings was 58 TWh in the year 2011. About 75% of it is created by SDFH, specifically by buildings which were built before 1970 (42%), although these specific buildings only supply 29% of the residential surface. As SDFH have the highest energy demand in relative as well as in absolute terms, these buildings could be a good starting point for the transition to a low carbon economy.

Figure 24 Total heating energy demand for the different building types and construction periods in GWh/a



S: based on Müller, 2015.

5.3.3 Technologies with potential for substituting current technologies

Potential (breakthrough) transition technologies are either a refurbishment of the current stock or demolishing the current stock, and replacing it by passive or plus-energy buildings, which do not need energy any more or even supply energy (in Figure 20 these technologies are located below the horizontal zero-energy-axis, i.e. in the quadrant with negative energy flow).

For the exemplary application we choose refurbishment to better insulated buildings as measure to substitute current technologies with new ones. More precisely we aim at improving energy intensity U/S by v (=ΔU/S), which results in a higher energy productivity (S/U).

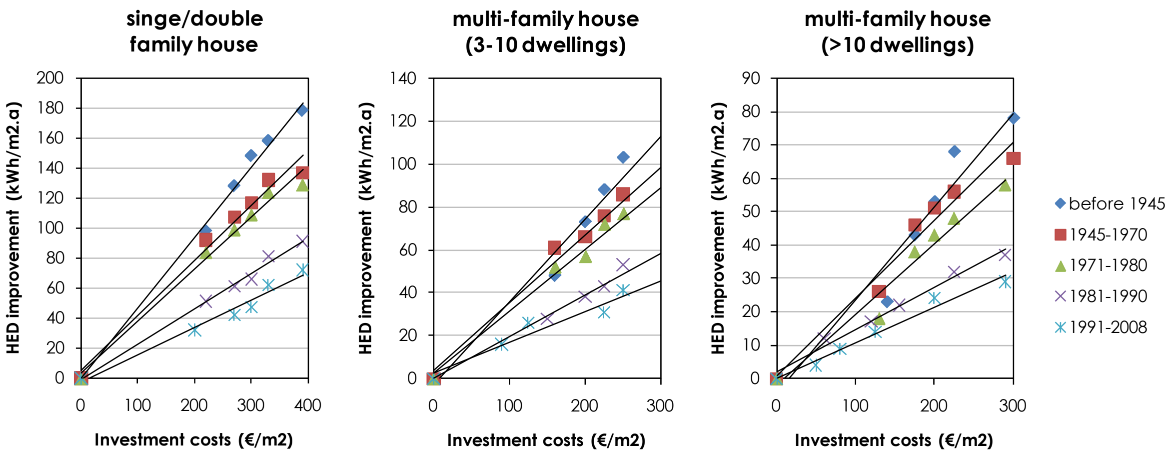
5.3.4 Cost of changing to new technologies/capital stock

Regarding the costs of switching to a new technology, we are interested in the required changes of the current cost structures. Thus, for the example of refurbishment, we focus on the *additional* costs which arise when refurbishment includes thermal improvements (i.e. the difference between the costs for a thermal renovation and maintenance costs which would be necessary anyway).

Therefore, the costs for changing to a new/better technology or capital stock are the additional investment cost in €/m² for an improvement in heating energy demand (HED) in kWh/m². This relationship is the one we have defined as function i(v) in section 5.2. As this relationship is set within a context full of complex interdependencies, its thorough analysis requires a level of detail that is beyond the one possible in the course of setting forth the research plan in the present document. What we can supply here, nevertheless, is an exemplifying illustration of the underlying basic concept. For this purpose we specify function i(v) from section 5.2 in the following.

For each of the three building types and the five building periods, these functions are estimated as linear functions, based on Müller (2015), and are given in Figure 25. We see that for older buildings investment requirements are less costly (per quality improvement gained) than for newer buildings, especially for the type SDFH built before 1970.

Figure 25 Additional investment costs for heating energy demand improvements



S: based on Müller, 2015.

5.3.5 *Compare energetic and economic effects across technologies*

We start the comparison of energetic and economic effects between the currently used technology (current stock with respective HED) and new technologies (refurbished stock) for the example of SDFH (1945-1970).

In a first step we carry out a comparative static analysis, normalised to the chosen proxy of 1 m². In a second step we then extend the analysis in a dynamic way and apply it to the total stock of the same building type (SDFH, 1945-1970) until 2050.

When comparing a future point to the current situation, some functionality specific assumptions are needed. For the example of refurbishment of SDFH (1945-1970) we assume:

1) Target for energy intensity: 50 kWh/m2.a which needs an improvement of 122 kWh/m2.a
2) Investment costs (subject to function in Figure 25): 318 €/m2
3) Energy price 2011: 0.15 €/kWh heating energy
4) Real energy price increase: +1% p.a.
5) Interest rate: 4%
6) Financing period: 30 years

Table 3 summarises the model parameters and the results of the analysis. For this specific example we see that annual user cost savings per m2 are 9€ in 2050. Thus from a user cost perspective the transition would be economically reasonable.

Table 3 Comparative static analysis of refurbishment of SDFH (1945-1970)

	2011	2050	Unit	model parameters
Energy intensity	172	50	kWh/m2.a	U/S
Energy productivity	0.01	0.02	m2/kWh	S/U
Improvement of energy intensity		122	kWh/m2.a	v
Investment cost for improvement		318	€/m2	i(v)
Energy price	0.15	0.22	€/kWh	p
Value of energy savings		27	€/m2.a	v*p
Annuity factor for investment		0.06		a
Annualised user costs for improvement by refurbishment		18	€/m2.a	n
Net user cost savings		9	€/m2.a	h

However, this static framework does not allow for analysing the transition process over time, which is crucial if we want to know e.g. the point in time when net user cost savings turn positive.

We thus carry out the analysis for the same building type (SDFH, 1945-1970), in a discrete dynamic manner. Therefore additional assumptions are necessary:

- Annual demolition rate: 0.5% p.a.
- Target of refurbishment of the remaining stock in 2050: 70%
- Refurbishment rate (diffusion function): We create a function which is calibrated such that the annual refurbishment rate in 2015 is 4% and is decreasing afterwards. (see Figure 26).

Figure 26 Diffusion function for refurbishment

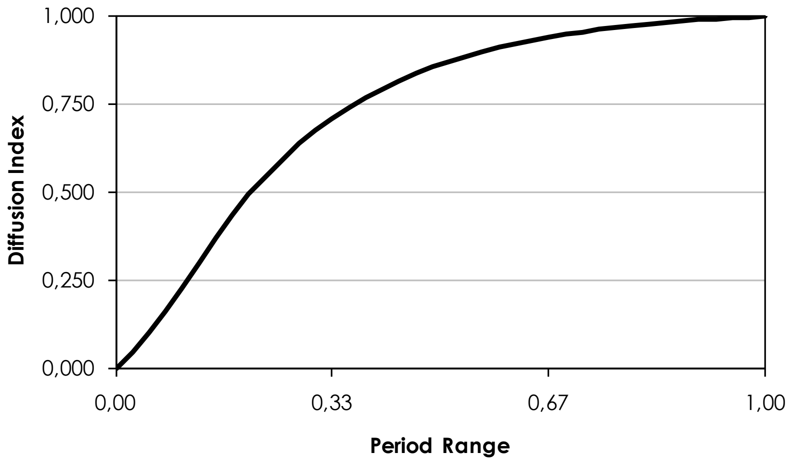


Figure 25 reports the thus generated diffusion function. The stock of (old) buildings (built 1945-1970) develops as given in Figure 26, with demolition reducing the overall stock over time, and the composition of this stock shifting towards a refurbished one.

Figure 27 Development of stock (SDFH, 1945-1970) until 2050

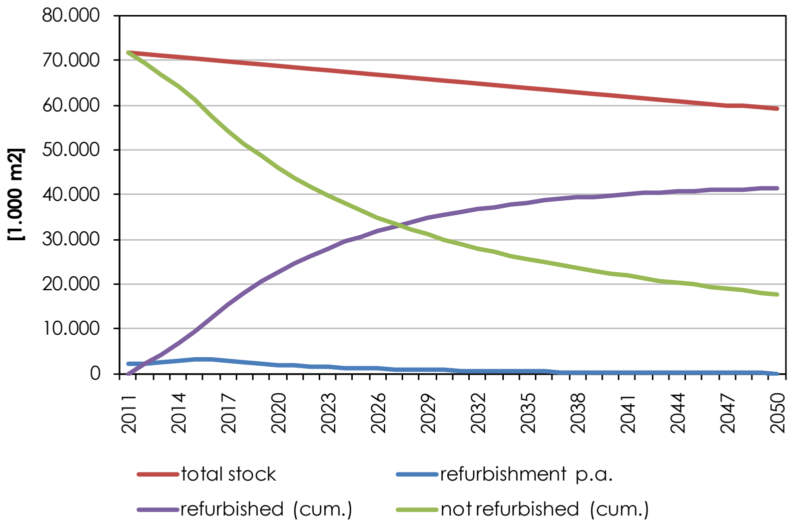
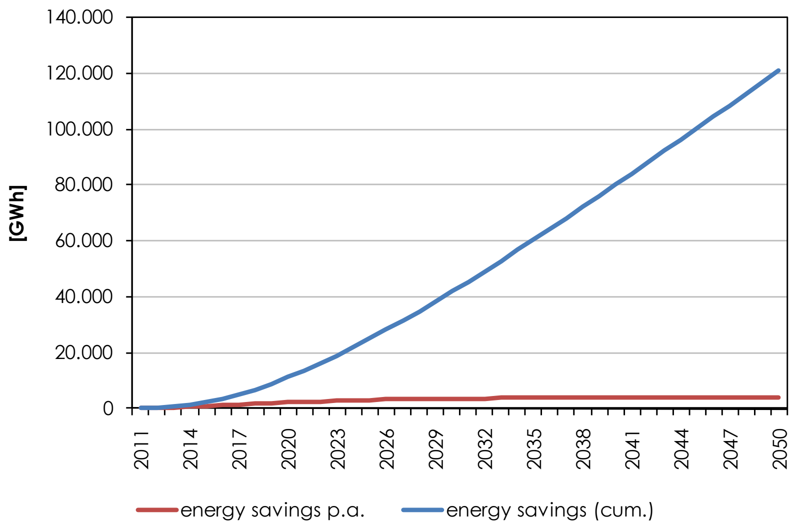


Figure 28 Annual and cumulative energy savings until 2050 from refurbishment (SDFH, 1945-1970) until 2050



The refurbishment succeeds in energy savings that are depicted both per year and cumulated in Figure 28.

The final additional ingredient to the economic analysis over time is investment costs, as given in Figure 29, with high and slightly rising investment initially, and declining rates assumed thereafter.

Figure 29 Annual and cumulative investment requirements for refurbishment (SDFH, 1945-1970) until 2050

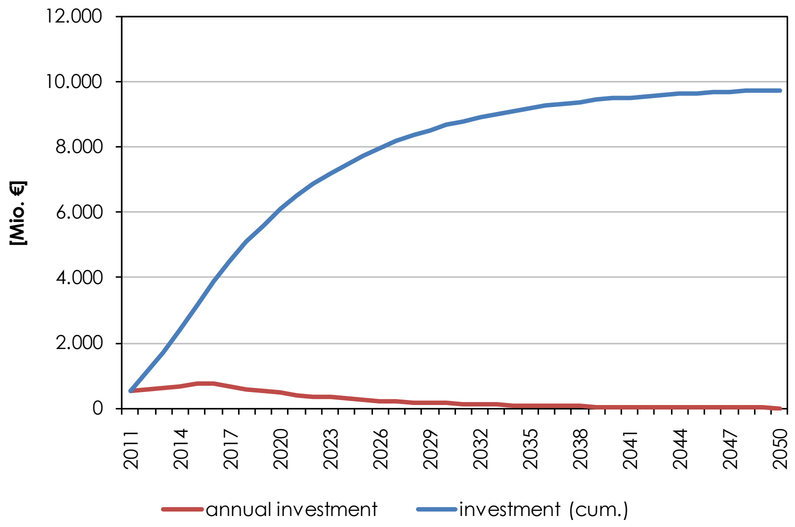
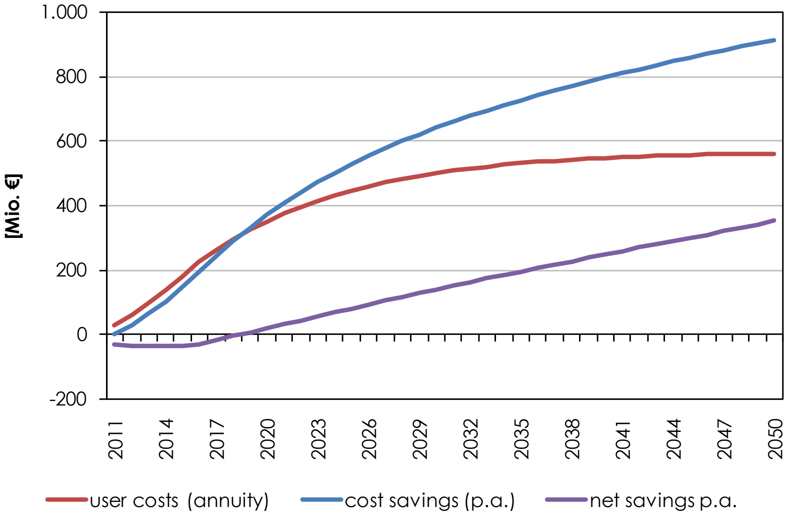


Figure 30 Annual user costs, user cost savings and net savings from refurbishment (SDFH, 1945-1970) until 2050



Combining all of this information in user cost analysis, we find that the point in time when (operating) cost savings begin to outbalance investment costs is well within the first decade of this transition. Net cost savings continue to rise thereafter.

5.4 Next research steps

In order to be able to evaluate transition options, a better understanding of both the current state and potential new ways to serve functionalities is required. Concrete tasks to this end include:

- Definition of functionalities
  - Give a clear and precise definition of all core functionalities
- Definition of respective proxies to measure functionalities.
  - Define carefully how to measure each functionality using proxies. This allows comparability for substitution[16].

    Examples for proxies:
    - Shelter: keeping 1 m² residential area at 21°C
    - Mobility: As the actual objective is "Access to persons, goods and services", traditional proxies, e.g. person-km, are misleading. What if we investigate the

[16] Note: If the unit of measurement changes, this may be an indicator for systemic changes. For further insights trace back energy and resource demand as well as emissions with respect to the proxy, i.e. follow the steps of the cascade structure of the energy and emission system backwards: that is from functionality to emissions; for energy related functionalities this means to trace back the energy cascade: functionality – energy service – useful energy – final energy consumption – primary energy.

technology 3D-teleconferencing? This technology makes passenger transport obsolete in some cases. A proper proxy may be "talk to a visible person for 1 hour".

- Development of an adequate analytical system
    - The deepened understanding of the structure of (economic/energy/emissions) systems requires a corresponding analytical framework that is able to simultaneously capture stock and flow elements.
- Identification of high-potential breakthrough technologies and respective costs
    - The availability of technologies, in particular breakthrough types, needs to be analysed, leading to data requirements for breakthrough technologies
- Identify at which levels transitions can occur
    - Taking the functionalities as given, transition can happen at different points in the spectrum of transition from marginal changes to radical changes:
        - Efficiency improvements within a technology: (e.g. more efficient diesel engines reduces losses between final energy and useful energy)
        - Change of the technology itself(e.g. use electric vehicles instead of conventional cars)
        - Change of the proxy to serve a functionality (e.g. physical transport may become obsolete by introducing 3D teleconferencing)
- Identify the extent of possible substitution
    - The quantitative relevance to substitute other resources with break-through technologies, in particular energy, needs to be analysed (also reflected in the diffusion rate).
    - By how much can new technologies substitute current technologies? What are the limits of substitutability?
        - e.g. 3D teleconferencing cannot substitute 100% of passenger transport but a fraction of it
        - e.g. electric cars (currently) have a limited range
        - the very long-term perspectives as to resource constraints (e.g. land for biomass and nutrition), but also investment costs and the sectoral structure of the national economy compared to the current state.
- Identification of cost profiles for current and future technologies
        - User costs: For an economic assessment user costs are relevant. For the evaluation of transition options user cost profiles are desirable for comparability. Operating costs relate to final resource/energy consumption in physical terms determined in Tier 1. Investment costs relate to costs occurring

with changes in capital stocks. Sensitive parameters are prices used for the long run transition analysis.

- Quantification of macroeconomic implications of transition options
    - For a macroeconomic assessment of transition options indirect effects (sectoral interdependencies, factor market feedbacks) need to be acknowledged, for both environmental (GHG emissions) and socioeconomic (economic activity, employment level, inflation, ...) impact analysis. For the evaluation of transition options these sectorally detailed effects, as well as their net aggregate implications are crucial in comparing different options for society. Applying an input-output model as core element can well serve this objective.
- Reveal all necessary inputs needed (energy, non-energy, capital, labour)
- Connection to Tier 3 (Institutional framework):
    - The institutional framework (Tier 3) may induce changes in economic structures, such that
        - User costs implemented at Tier 2 relate differently to physical parameters of Tier 1 (when e.g. incentive systems are changed by new financing options of building insulation). This may affect both investment and operating costs.
        - Macroeconomic feedback mechanisms change (when e.g. a basic income changes labour supply – Tier 3) which need to be adequately depicted (mutually consistent) at Tier 2.
    - Identification of how institutions can foster transition processes making use of economic incentives
- Data base screening
    - In order to integrate the suggested methodologies into an open source model a thorough screening of existing databases is necessary as well as the identification of additional data requirements.

6 Tier 3: The institutional layer of a deepened structural modelling approach

Compared to traditional modelling approaches ClimTrans2050 proposes an extended mindset for modelling that integrates the institutional layer more explicitly into the overall framework. Different institutional elements are also integrated in mainstream modelling, however, they typically show a strong focus on market mechanisms. To overcome this shortcoming of mainstream modelling, the ClimTrans2050 Research Plan adopts a broad perspective on institutions and especially emphasises the role of llifestyles and consumption patterns.

The institutional layer in its comprehensive understanding determines the framing in which socio-economic activities take place, and thus shapes what form they take as well as it determines their GHG emissions. In the context of the functionality approach it ultimately co-determines the level of functionalities and which combinations of stocks and flows are chosen for satisfying them. The institutional layer is an enabling factor for functionalities and for transformation processes. In order to highlight the relevance of the different aspects of the institutional layer and particularly emphasising the role of non-price mechanisms ClimTrans2050 proposes a separate tier to address the institutional setting. The rationale for this is to augment transparency with respect to instruments and mechanisms in modelling.

The institutions modelled in Tier 3 transmit to Tier 2 and Tier 1. In order to illustrate this transmission process one can use efficiency standards as an example. For a certain functionality more stringent regulation would translate into an investment demand, changing (the quality of) stocks. The functionality then would be provided by a new combination of stocks and flows. The respective effects of the economic activities in Tier 2 translate into changes in emissions in Tier 1.

The institutional layer is not to be considered as a separate module, but as a different yet integrated modelling step. The aim is not to strive for a "supermodel" that encompasses all thinkable aspects of institutions. A series of modules would be more feasible to capture the role of institutions for transformation processes and emissions. However interactions between model modules need to be considered, i.e. one has to assess whether a linkage of model modules is advisable or necessary.

Giving special emphasis to the role and potentials of different institutions by deliberately distinguishing between the three tiers is one of the cornerstones of the ClimTrans2050 Research Plan. In a nutshell this approach has the following merits:

- It encourages broadening the scope of institutional elements and new practices in modelling.
- It puts special emphasis on non-market mechanisms.
- It increases the transparency of the impact of different institutional elements on the transition process towards a low carbon economy.

- The ClimTrans modelling framework links the physical layer (Tier 1) and the economic layer (Tier 2) to the institutional layer (Tier 3).

6.1 Elements of the institutional layer

How the institutional layer (Tier 3) can be understood as building block of the deepened structural modelling approach as developed in chapter 2 is illustrated in Figure 31. The main interest as expressed here is the transmission process of the mechanisms from the institutional layer to the economic and physical layer. The ClimTrans2050 Research Plan aims at a series of model modules along the three tier structure that supports the development of an open source model suited to capture transformation processes.

The institutional setting is given at Tier 3, including aspects such as which allocations are organised via markets, where and what norms or standards are set (social, environmental, technological, labour), or which specific policy instruments are implemented.

Tier 2 as well as Tier 1 in contrast is a representation of the result of any such setting given at Tier 3, from a socio-economic and emissions perspective. It is a socio-economic and physical depiction of what is defined and modelled at Tier 3. Tier 2 thus e.g. can inform about the impacts of the settings defined at Tier 3 (such as specific policies) on induced economic activity and in turn about employment and output effects both in the investment and operating phase. Obviously this also brings about feedback effects, e.g. disposable income or tax revenues. Policy model modules implemented at Tier 3 can draw from this information.

In the following we reflect on institutional elements that are of high relevance in the context of long run decarbonisation processes. This comprises heterogeneous elements that encompass both market based and non-market based instruments and mechanisms:

- Llifestyles: Llifestyles are reflected in consumption patterns that relate to certain production structures and ultimately greenhouse gas emissions. Although research (e.g. IPCC, 2014) points at the crucial role of lifestyles for climate change mitigation, they are often not explicitly addressed in modelling.
- Social dimension: The social dimension includes e.g. the labour market design, distributional aspects, or education. These aspects are already taken up in different level of detail and different way in existing models. Knowledge already available can serve as input for model modules in the deepened structural modelling approach.
- Non-market based instruments: This group of instruments comprises command-and-control instruments like standards. Usually these instruments are not the main focus in traditional economic modelling approaches that typically put a stronger emphasis on changes in relative prices. This category of instruments, however, may exert considerable changes in economic activity and economic structures.
- Market based instruments: They are represented broadly in existing economic models and are e.g. modelled as taxes, permits, or subsidies. Typically the effect of market based instruments is modelled as causality between price changes and changes in

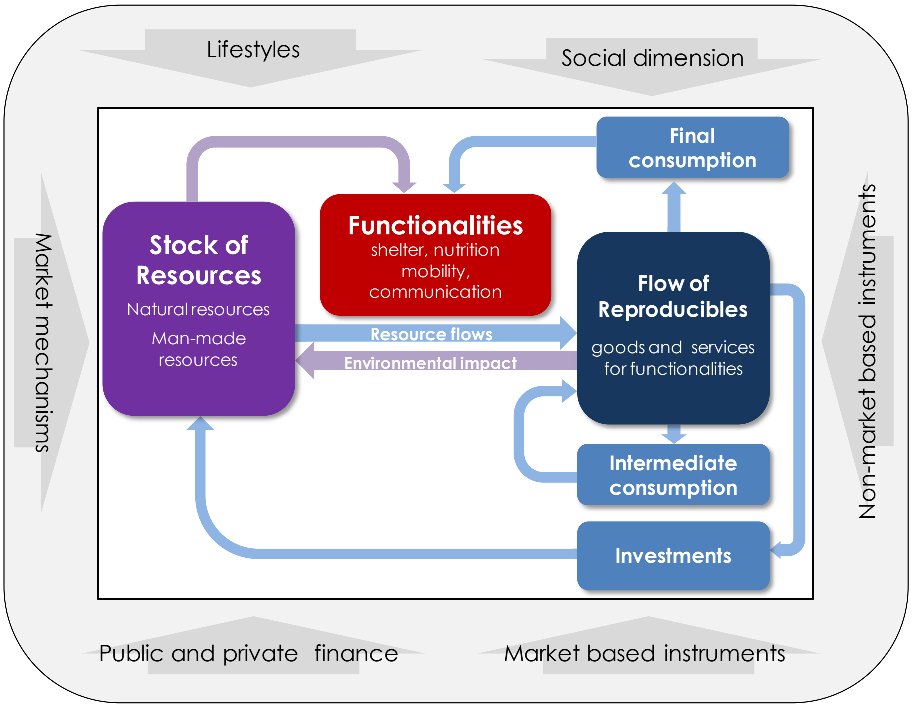
production and consumption patterns. Interlinkages with other regulations e.g. standards is in this context frequently concealed. Explicitly addressing the institutional layer facilitates to focus on these aspects.

- Public and private finance: The public sector is of high relevance and has a large potential with respect to changing capital stocks and infrastructure. Hence, for low carbon transition modelling it needs to be addressed in sufficient detail; e.g. with respect to the tax structure or public investment. For user costs, as emphasised in the ClimTrans2050 Research Plan, aspects of private finance like amortisation periods need to gain in importance in modelling. This concept is standard for investment decisions, but not firmly integrated in macroeconomic models.
- Market mechanisms: They represent the role of markets for economic activities.

This list above makes clear that the institutional layer as part of the deepened structural modelling framework covers a broad range of issues including the role of markets in the private sector and the issue of market failures which require corrective actions by the public sector (command and control, price instruments), institutional innovations and lifestyles.

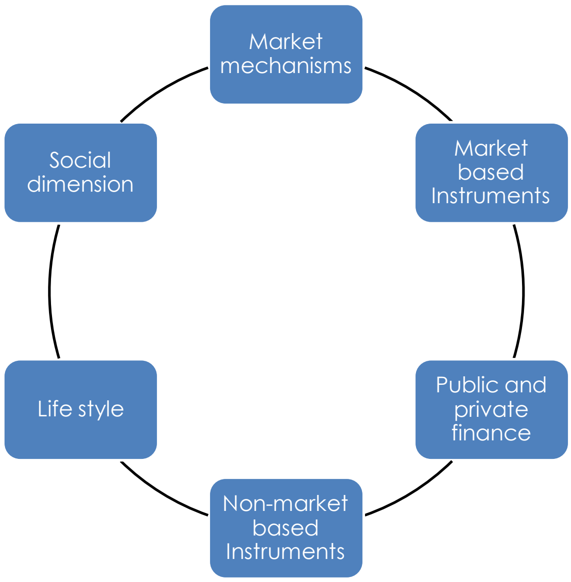
Modelling behavioural change, though of key importance for assessing long term transformation processes, is challenging and may require novel approaches. Consumption patterns e.g. can often not be explained solely by economic considerations but are also driven by status, habits and customs. To integrate (existing) research on these aspects into a comprehensive open source model will be one main step in model development.

Figure 31 The institutional layer of a deepened structural approach



The above described elements cannot be interpreted as being independent from each other. From a modelling perspective it seems more feasible to tackle the aspects in a series of separate model modules due to e.g. the high level of complexity or high data requirements. However not only feedback effects between the different tiers of the model need to be accounted for but also the interlinkages between separate elements of the institutional layer, as illustrated in the figure below.

Figure 32 Interdependency of Tier 3 elements



The model modules in Tier 3 are not an end in itself but a means to define the setting triggering the transmission process to Tier 1 and Tier 2 and the prevailing respective economic and emission structure. Storylines for long run transition options need to be translated into a specific model setting and model inputs on all three tiers. Through the transmission process Tier 1 gives then the interpretation on the effect on emissions incorporating also the changes in Tier 2. Transformation options that aim at a specific emission target very likely will require an iteration process, i.e. after providing an institutional setting (Tier 3) and deriving the effects in Tier 1 and Tier 2) the parameters in Tier 3 will have to be adjusted (e.g. new instruments, change in scale of instruments).

6.2 Next research steps

The explicit distinction between the economic structure and the institutional setting is one of the innovative aspects of the modelling framework for an open source model proposed in the ClimTrans project. In this respect the following research gaps should stimulate efforts to widen the perspective in transition modelling.

- Specify detailed modules for the institutional elements of Tier 3.
- Define module interfaces that capture the interlinkages between instruments, behavioural or social changes (Tier 3) and that enable the quantifications of the impact on emissions via economic or technical parameters.
- Allow for and integrate disruptive events (e.g. BSE, bird or swine flu).
- Allow for and integrate social innovations and structural changes.

7 Web platform, model modules and model manual

One of the goals of the ClimTrans2050 project was to supplement the developed methodological concept with exemplary empirical model modules directed both at the modelling community and decision makers. The two model modules presented at the interactive web platform are illustrations of the energy cascade and Austrian reduction paths in a global context following the rationale as developed in this research plan.

Details on the model structure for the energy system are described in the ClimTrans2050 Working Paper No.2 (Schleicher et al., 2016 in the appendix). The methodological background for the Austrian emission pathways is laid out in chapter 3.

7.1 Web platform

In the **ClimTrans2050** project we provide an internet platform http://climtrans2050.wifo.ac.at/. This homepage serves three purposes:

- Background information on the project and project team
- Access to project outputs
- Exemplary model modules with interactive elements

The interactive section of the web platform is the first step for the development of an operational open source model based on the proposed new understanding of modelling transformation processes. In this sense the research plan provides manifold suggestions and broad basis for further research.

With respect to the energy system, the implementation as a web tool offers the cascade structure of the energy system in an easily accessible way. The low access barriers allow especially stakeholders, and other non-modelers, visualization and modification possibilities of all relevant information. For the modelling community it provides a rich database and the demonstration of the translation of the concept of the energy cascade into an empirical structure. Users can create visions of the future of the Austrian energy system. All decisions are reflected in the composition of energy use, energy supply and induced CO_2 emissions. The findings are visualized and can be compared with past development.

A second exemplary model module allows the visualisation of Austrian reduction paths in a global context as conceptualised in chapter 3.

The web tool is implemented as a responsive web application, which can be used on every contemporary computer, tablet and smartphone. All the chosen options are locally persisted and remembered over multiple sessions.

7.2 Web platform module on the energy system

In chapter 4.1 already the basic characteristics of the energy system following the functionality approach is laid out. The model manual starts (ClimTrans2050 Working Paper No.2, Schleicher et al., 2016) from this conceptual framework and details the model structure for empirical implementation. This shows especially in a more detailed formal model representation as well as a coherent linkage with the economic (Tier 2) and institutional (Tier 3) layer.

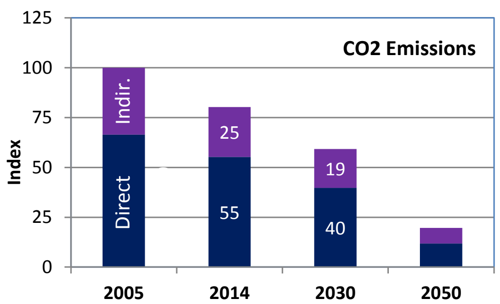
The precondition for the application of the functionality approach is a database that provides information on energy use categegories. For Austria this is provided by Statistics Austria in the Useful Energy Balances[17]. According to this database we are able to deal with the following energy related functionalities as already identified in chapter 4.1.:

- Low Temperature Heat
- High Temperature Heat
- Stationary Engines
- Mobile Engines
- Lighting and Electronics

We are able to partition CO_2 emissions fully to these functionalities. This is done by adding to the CO_2 emissions from the fossil energy flows needed for a particular functionality also the indirect emissions via the consumption of electricity and heat and the related distribution losses.

Figure 33 indicates how an emissions path could look like that reduces 80% of emissions by 2050 compared to 2005.

Figure 33 CO_2 Emissions – direct and indirect emissions

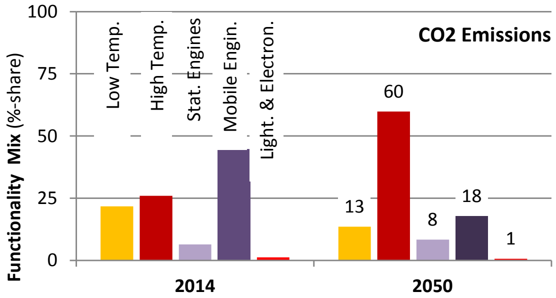


Source: ClimTrans2050 Working Paper No.2 (Schleicher and Hofer, 2016).

Figure 34 indicates the distribution of these emissions according to the functionalities. Currently this emissions peak in mobile engines, i.e. transport activities. By 2050 the remaining emissions could be dominated by functionalities related to high temperature heat, i.e. energy intensive industrial processes.

[17] http://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/nutzenergieanalyse/index.html

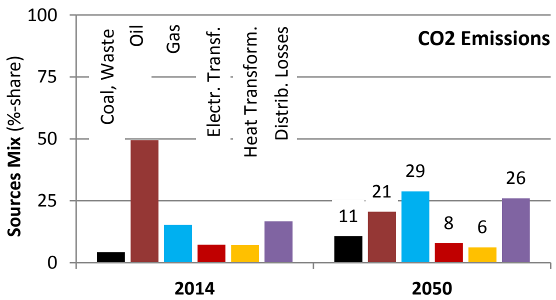
Figure 34 CO_2 Emissions related to functionalities



Source: ClimTrans2050 Working Paper No.2 (Schleicher and Hofer, 2016).

Figure 35 finally depicts the distribution of these emissions according to the types of energy used for providing the functionalities. Currently these emissions mainly originate from oil products. By 2050 the remaining emissions show peaks in gas and distribution losses.

Figure 35 CO_2 Emissions related to energy types



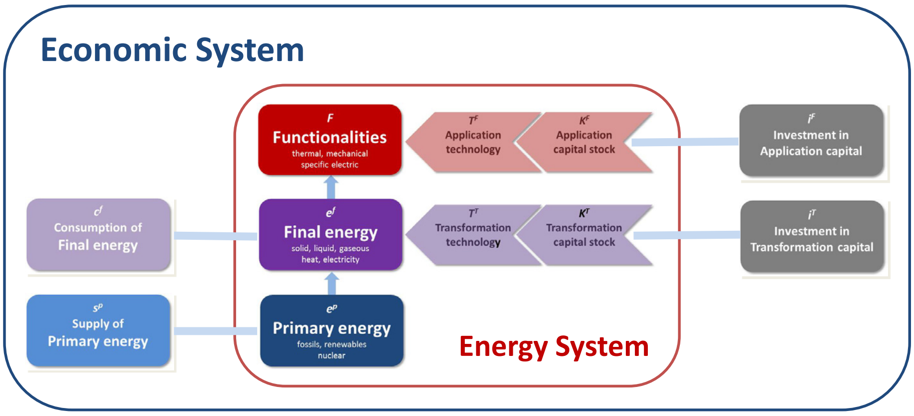
Source: ClimTrans2050 Working Paper No.2 (Schleicher and Hofer, 2016).

7.2.1 Links betweenthe energy system and the economic system

The energy system of layer one is embedded with the following linkages into the economic system (Figure 36), which we identity as layer two in our modeling framework:

- Energy flows, as final and primary energy, e^f and e^p, respectively.
- Investments into the capital stocks for application and transformation technologies.

Figure 36 Embedding the energy system into the economic system



Source: ClimTrans2050 Working Paper No.2 (Schleicher and Hofer, 2016).

Both types of physical energy flows of the energy system are in the economic system converted into monetary units via appropriate prices.

Assuming a representative energy price p^e, then final energy e^f shows up in the economic system as consumption of energy c^e

(2.1a) $$c^e = p^e \cdot e^f$$

and primary energy e^p corresponds in the economic system as energy supply s^e

(2.1b) $$s^e = p^e \cdot e^p$$

Two investment activities in the economic system are relevant for the technologies of the energy system and its related productivities, namely investments into the application and the transformation capital stock.

Investments i^F in the capital stock for application technologies are determined by changes of this capital stock ΔK^F and replacement investments r^F:

(2.2a) $$i^F = \Delta K^F + r^F$$

Similarly investments i^T in the capital stock for transformation technologies result as:

(2.2a) $$i^T = \Delta K^T + r^T$$

We proceed by partitioning the economic system into two sectors:

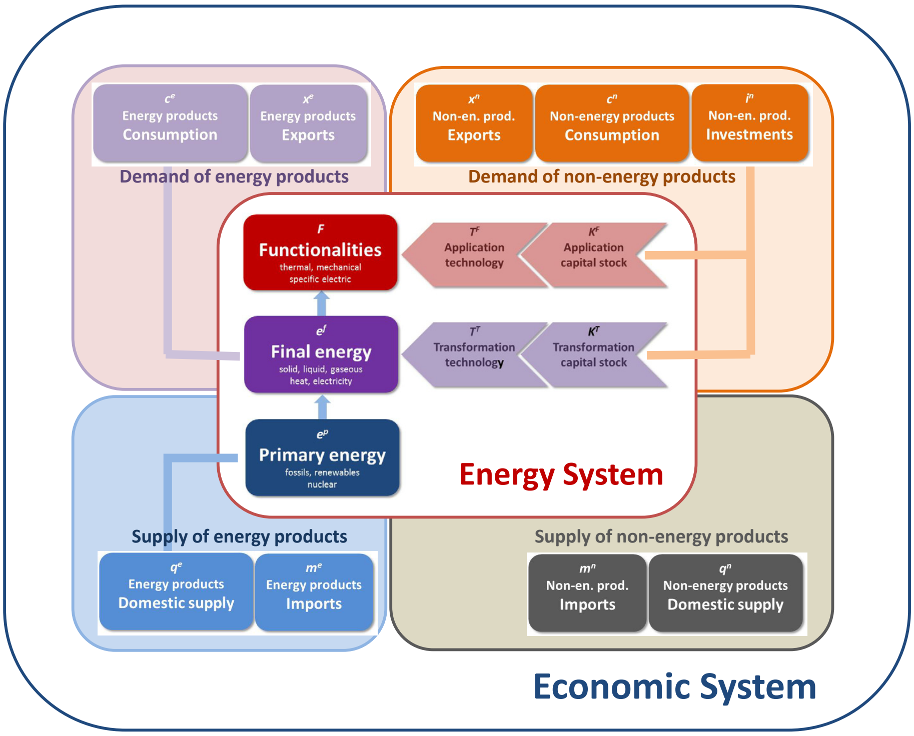
- The energy sector covers all activities that relate from the supply of primary energy to the provision of functionalities.
- The non-energy sector deals with the remaining activities of the economy and may be further disaggregated into subsectors.

At this point of the exposition of the deepened structural modeling framework it seems worth reminding that so far we have only proposed relationships that describe either physical identities, as in the energy system of layer one, or monetary identities without claiming any causalities or behavioral assumptions. This will explicitly be dealt with in layer three.

We therefore do not postulate, e.g., in layer two of our modeling framework that demand will equal supply either in the energy or in the non-energy sector.

Figure 37 visualizes how the energy system interacts with the economic system. The main linkages are the flows of final and primary energy and the investments that determine the productivity of the application and transformation technologies.

Figure 37 Interactions between the energy system and the economic system



Source: ClimTrans2050 Working Paper No.2 (Schleicher and Hofer, 2016).

7.3 Web platform module on GHG emissions and reduction targets in a global context

The visualisations of the global and Austrian historical GHG emissions as well as of the reduction targets presented in sections 3.2 and 3.3 are available on the project's web platform offering a broader overview of the emissions and reductions leading towards different warming targets. Table 4 below summarises the content[18] of this exemplary model module.

[18] Data sources are specified in the module.

Table 4 Content of the exemplary model module on historical GHG emissions and reduction targets

Perspective	Historical emissions	Warming targets	Reductions starting in:	Emissions reductions obligations	Scenarios of future emissions
Global	Technospheric, LULUCF	2°C 3°C 3°C - 4°C ≥ 4°C	1990 2000 2010	n.a.	IEA 2°C, 4°C and 6°C scenarios (CO_2 only)
EU 27	Technospheric and LULUCF (both with and without emissions resulting from international trade)			Kyoto protocol, post-Kyoto pledges, EU effort sharing	
Austria				Kyoto protocol, EU burden sharing, EU effort sharing	WEM and WAM scenarios (all GHG) Emissions resulting from energy related functionalities (CO_2 only)[19]

7.4 The value added of the deepened structural modelling approach

In a nutshell basically two extensions characterize the new energy eco-nomics:
The first extension discovers the internal structure of an energy system which exhibits a cascade sequence:

- Functionalities
- as the energy services related to thermal, mechanical and specific electric tasks are the ultimate purpose of an energy system.
- Technologies
- as for applications in buildings, mobility, and production, and for transformations to electricity and heat determine the related energy flows.
- Energy mix
- as the partition of energy into fossils and renewables has impacts in particular as to greenhouse gas emissions.

The above described core of an energy systems, which is characterized by its physical characteristics, communicates in an onion-like structure with the economic sphere and with the institutional and behavioral sphere.
Thus we can identify three encompassing layers for a comprehensive characterization of an energy system.

- The physical layer

[19] Interactive option: CO_2 emissions from energy related functionalities for user-specified energy mix.

- depicts the cascade ranging from functionalities to energy flows and their mix depending on the choice of application and transformation technologies.
- The economic layer
- interacts with the physical layer via consumption of energy and investments into stocks that are relevant for energy productivity and energy efficiency.
- The institutional layer
- provides mechanisms for coordination and incentives, as markets and regulations, and considers behavioral attitudes.

7.5 Next research steps

- Specify and compile detailed modelling and data for the economic and institutional layer.
- Modeling the interfaces that capture the interlinkages between different instruments and the physical layer.
- Quantifications of the economic impacts.
- Modeling of disruptive events and compilation of necessary data and parameters to capture them.
- Extend the empirical basis to model modules of other functionalities.

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9 Appendix

9.1 Appendix A: ClimTrans Working Paper No.1: Assessing current modelling practices.

Assessing current modelling practices

ClimTrans2050 Working Paper No.1

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Abstract

Existing energy- and climate-economic modelling approaches are increasingly seen with skepticism regarding their ability to forecast the long term evolution of economies and energy systems. The economic, climate and energy sphere are highly complex non-linear systems and so far most often only poorly dealt with when assessing the transition pathways leading to a desirable future. This Working Paper reports a structured meta-analysis of state-of-the-art national and international energy-economic modelling approaches, focusing on their ability and limitations to develop and assess pathways for a low carbon society and economy. In particular, we set out to identify those existing models and/or model components/modules which could be of interest in developing a research plan for the creation of an open source model for analysing a national transition to a low carbon society by 2050, here more specifically applied for Austria. We find that existing methodological approaches have some fundamental deficiencies that limit their potential to understand the subtleties of long-term transformation processes. Therefore, we suggest that a methodological framework for analysing long-run energy and greenhouse gas emission system transitions has to move beyond current state of the art techniques and simultaneously fulfill the following requirements: (1) dynamic analysis, describing and investigating explicitly the path between different states of system variables, (2) specification of details in the energy cascade, in particular the central role of functionalities that are provided by the interaction of energy flows and corresponding stock variables, (3) a clear distinction between structures of the energy systems and (economic) mechanisms and (4) ability to find optimal pathways. Furthermore, a crucial task in modelling is to specify whether each model element is determined endogenously or exogenously, ideally governed by the demands of the underlying question to be answered.

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1 Introduction

This working paper serves as a background paper on current energy-economic modelling practices for the research project ClimTrans2050. The guiding question for the ClimTrans2050 project is: **What kind of modelling framework is most suitable for assessing the long-term transformation processes needed to drastically reduce Austria's GHG emissions**? The aim of Work Package 1 of this project is to provide a structured meta-analysis of state-of-the-art national and international energy-economic modelling approaches with respect to their ability and limitations to develop pathways for a low carbon society and economy, both in total and for the main sectors contributing to greenhouse gas emissions. The underlying question of this working paper is therefore which models and/or model components/modules are most suitable to be integrated in an open source modelling framework for the analysis of a low carbon energy transition.

In recent years, the number of energy-economic models has grown tremendously, to a large extent due to expanding computing possibilities. At the same time existing energy- and climate-economic modelling approaches are being confronted with increasing skepticism with respect to their ability to forecast the long term evolution of economies, which are highly complex non-linear systems, and to assess the transition pathways leading to that future state (Pindyck, 2013; Pindyck and Wang, 2013; Rosen and Guenther, 2015). Moreover, the question arises whether it is feasible at all to predict an economy's future evolution in the presence of deep or fundamental uncertainties (variations around expected system behaviour that cannot be quantified) and catastrophic risks (Rosen and Guenther, 2015; Scrieciu et al., 2013).

The existing models to assess energy- and climate-economic research questions vary considerably and the question arises which model is most convenient for a certain purpose or situation, in our specific context the long term transition to a low carbon energy future. A classification scheme can provide insight in the differences and similarities between energy-economic models and thus facilitates the selection of the proper models or specific modules to assess the problem at hand (van Beeck, 1999).

In a first step we suggest a set of characteristics or dimensions derived from the existing literature and from discussions within the ClimTrans2050 project team for a **categorisation of the different modelling approaches** focusing on characteristics that are relevant for a model to be suitable for long term transition analyses. In a second step we **identify specific "prototypical" models** of different model classes that have been used in the analyses of energy policies in the context of Austria and Europe, which could be of interest in developing a research plan for the creation of an open source model for analysing Austria's transition to a low carbon society by 2050. In a third step, we **evaluate these different energy-economic modelling approaches in terms of their strengths and weaknesses to carry out low carbon transition analyses** and discuss their advantages and disadvantages to that end.

2 Characteristics for the classification of energy-economic modelling approaches

A general characteristic all models share is that a model always is a purposeful and simplified representation of aspects of reality (Starfield). Purposeful in that sense, that a model is always developed in order to answer a specific research question. For example, there is no generic forest model applicable in all circumstances, as the concrete model design always depends on the specific research question (e.g. optimal harvesting, forest soil, species, forest fire risk, etc.). Simplification in that sense, that first, the just identified concrete purpose of a model already paves the way for a simplified representation of this specific aspect of reality, and that second, real world constraints, such as limited time and financial resources, require further simplifications.

Besides this general characteristic there are many individual characteristics or criteria which differ substantially between modelling approaches. Hence, it seems reasonable to set out to classify existing energy-economic modelling approaches and specific models to allow for an identification of the most appropriate approach for the problem setting at hand – out of the multitude of existing models out there. While there have been some attempts in the literature to classify existing energy models (Grubb et al., 1993; Herbst et al., 2012; Hourcade et al., 1996; van Beeck, 1999), no systematic classification of energy-economic models serving the purpose of analysing energy transition pathways has been carried out so far. Hence, by relying on the existing literature on energy model classification and by building upon the discussions of the ClimTrans2050 project team, we identify the 8 most important characteristics and dimensions to classify energy-economic models and present a systematic classification of the existing relevant modelling practice. The present categorisation exercise differs from the existing literature in that we are focusing on the models' suitability for long term transition analyses. Hence we put special emphasis on certain (sub)characteristics, mainly linked to the model structure and modelled mechanisms, which are crucial for our purpose. The 8 dimensions/characteristics include (cf. van Beeck, 1999):

- The general purpose and intended use
- The analytical approach and conceptual framework (Top-Down, Bottom-Up, Integrated Assessment/hybrid energy-economy model)
- The model structure and external assumptions: modelled mechanisms and assumptions (implicit/endogenous and explicit/exogenous mechanisms/assumptions; technological details). How an energy-economic model treats the following features/mechanisms is crucial for its ability to carry out long term transition analyses.
    - (disruptive/non-linear) technological change
    - technological detail
    - international (trade) relations
    - detailed representation of the energy cascade
    - price & market mechanisms

  - economic feedbacks and rebound effects
  - non-market mechanisms (such as non-market damages and climate feedbacks)
  - structures vs. mechanisms – how do mechanisms influence structures
  - stocks vs. flows
  - financing/investment (of e.g. energy efficiency measures)
  - institutions
  - behavioural mechanisms
  - out of equilibrium situations
  - risk and uncertainty
- The time horizon
- The underlying methodology (Optimization, Simulation, Econometric, Equilibrium etc.; estimation vs. calibration)
- The treatment of path dynamics (Comparative Static VS Dynamic ("path explicit"))
- Development of a baseline/reference scenario
- Geographical and sectoral coverage
- Data requirements

The listing of these characteristics already follows an ordinal/hierarchical logic modelers should follow when setting out to identify the most appropriate approach for their very specific research questions. Modelers first have to be clear about the general and more specific purpose of the model. Next the analytical approach has to be chosen, i.e. whether the eventual model should rather take a top-down or bottom-up or hybrid perspective. Closely related is the choice of the modelling structure which boils down to choosing internal and external assumptions, or more precisely, what mechanisms should endogenously be determined within the model and what mechanisms should be based on exogenous assumptions. Before choosing the specific underlying methodology of the model, a modeler should also reflect on the time horizon her model should be able to operate in. After deciding on all that characteristics and choosing a specific method, the most appropriate mathematical approach has to be identified. Finally, the geographical and sectoral coverage of the eventual model has to be decided upon and the data requirements assessed.

2.1 The purpose and intended use of energy-economic models

Modelling is a general kind of activity that follows certain principles independent on what is modelled and what technique is used. As mentioned above, a model is always a purposeful and simplified representation of an aspect of reality. Hence, models are usually developed to address specific research questions and are only applicable for the purpose they have been designed for. An application of a specific modelling technique for an inappropriate purpose may lead to significant misinterpretations of the problem at hand and eventually to poor policy recommendations negatively affecting real world socioeconomic systems. In the following we distinguish between general and more specific purposes of an energy-economic model.

General purpose

Hourcade et al. (1996) define as the general purpose of the model the different ways how the future is addressed in a modelling framework and distinguish between three general purposes which are also applicable in the case of energy-economic models:

- **Prediction or forecasting models**

  Many models are developed to try to "predict" the future and to estimate impacts of likely future events. This purpose imposes very strict methodological constraints on modelers as forecasting models require the establishment of a business as usual scenario against which future policy induced deviations from this best-guess future development can be assessed. This requires an endogenous representation of economic behaviour and general growth patterns. Such models are based on the extrapolation of trends found in historical data and try to minimize the usage of exogenous parameters. Models built for a predictive purpose are most suitable for short term analyses, since a number of critical underlying parameters (such as elasticities) cannot reasonably be assumed to remain constant for longer time frames. Hence, this approach is mainly found in short term, econometrically driven economic analyses.

- **Explorative scenario analyses models**

  Due to the inherent difficulties associated with the extrapolation of past trends in the long run, modelers might set out to "explore" rather than "predict" the future. An explorative purpose can be served by employing a scenario analysis approach. This requires the definition of different coherent visions of the future, determined by different values for key assumptions about economic behaviour, economic growth, population growth, (natural) resource endowments, productivity growth, technological progress etc. A reference or nonintervention scenario is developed and then contrasted to different policy or intervention scenarios. It is important to note that these alternative scenarios only make sense in relation to the reference scenario and should therefore not be analysed in isolation from it or in absolute terms. Furthermore, sensitivity analyses are crucial to provide information on the effects of changes in underlying assumptions.

- **Backcasting models**

  The basic concept of backcasting models is to look back from *desired futures*, which are developed e.g. in expert stakeholder processes, to the present, and to develop *pathways* for actions that have to be taken in order to reach these desired futures. The backcasting methodology allows for the identification of major (technological) changes and discontinuities that might be required to achieve a certain desirable state of the future.

Specific purpose

More specific purposes are linked to the aspects of the economy, energy system, or the environment a model focuses on. With respect to energy-economic models one could distinguish between models that serve the purpose of modelling energy demand, energy supply, economic or environmental impacts from energy supply or conducting project appraisals (van Beeck, 1999). Historically there has been a strong focus on single-purpose models, contemporary models often pursue an integrated approach. Demand-supply matching models and impact-appraisal models are two examples of multi-purpose energy-economic model approaches.

Also for the development of an integrated modelling framework for the analysis of a transition to a low carbon society, a multi-purpose approach constitutes a promising approach. A model constructed as a modular package would (1) allow for the selection of the most promising building blocks from different existing modelling frameworks to serve the more general purpose and (2) enable the user to select only those (sub)modules that are relevant for answering specific questions.

2.2 The analytical approach and the conceptual framework

Models for the analysis of an energy transition can also be classified according to their degree of detail. On the one end of the spectrum there are “bottom-up” techno-micro-economic models, which are built to describe economic sectors or sub-sectors (e.g. the electricity sector). These models are rich in (technological) detail and are well suited to simulate market penetration and related cost changes of new (energy) technologies, to present detailed pictures of plausible energy futures and to evaluate sector- or technology-specific policies. However, this technological detail comes at the cost of a limited representation of macroeconomic implications. Bottom-up models typically do not capture feedback effects with other parts of the socioeconomic system (e.g. other economic sectors, households, the public sector, macroeconomic relationships, the environment etc.).

On the other end of the spectrum there are “top-down” economic models with only limited explicit representation of alternative technologies using elasticities to implicitly reflect technological variability. They may even be more abstract and aggregated “integrated assessment models” (IAM) or “hybrid energy-economic models”, which strive to close the loop between a specific economic activity and the surrounding environment. Within the class of IAM one can further distinguish between “hard-linked” models which are built as one set of consistent (differential) equations, working within one closed model system, and “soft-linked” models which couple separate models and solve them sequentially using input/output exchange routines. In general, IAM allow capturing feedback effects between aspects of the system under consideration (economy, climate system, society, other environment). However, both types of IAM have shortcomings: Hard-linked models usually work on a very coarse level of detail by using (e.g. damage-) functions relating e.g. economic indices like a region's GDP and global mean temperature changes. Such simplifications are problematic as effects within the economic system cannot be revealed and they can hardly be used to account for singular events and catastrophic risks. Damage functions have often been calibrated based on limited expert judgment, which has implications for their validity (see the recent debate on Integrated Assessment Modelling and Social Costs of Carbon: e.g. Pindyck and Wang, 2013; Pindyck, 2013). Soft- linked models on the other hand allow for more detail; however problems may arise in convergence and consistency among the models used.

In general, the distinction between top-down and bottom-up models is of substantial importance, as both approaches tend to deliver different – sometimes even opposite – outcomes. The difference in model outcomes of top-down and bottom-up modelling approaches arises from the distinct ways how these models treat technological change, the adoption of new technologies, the decision making of agents and how markets and institutions operate (Hourcade et al., 1993). Grubb et al. (1993) associates the top-down approach with a "pessimistic" economic paradigm and the bottom-up approach with a more "optimistic" engineering paradigm.

Purely economic top-down models and much more so IAM have no explicit representation of technologies. In economic models technologies are regarded as a set of techniques by which a combination of inputs can be used to produce useful output, typically represented by production functions. Elasticities of substitution between different inputs in an aggregate technology production function are employed to implicitly reflect technological variety and in combination with an exogenous assumption of so-called "autonomous energy efficiency improvements" (i.e. efficiency improvements which happen w/o any explicitly modelled technological change) account for technological change in top-down economic models.

Engineering studies, on the other hand, start with a description of technologies, including their performances and direct costs, to identify options for technological improvements. From an engineering standpoint, the most energy efficient technologies have not been adopted so far and therefore an "efficiency gap" prevails, which could be closed by employing the most energy efficient technologies. The differences in outcomes eventually arise from the fact that the "optimistic" engineering bottom-up models tend to ignore existing constraints which hinder the actual adoption of most efficient technologies, such as hidden costs, transaction costs, implementation costs, market imperfections and macroeconomic relationships (Grubb et al., 1993).

A further distinction between bottom-up and top-down models can be drawn along the lines of data used in the different model analyses. While top-down economic models use aggregated data to examine interactions of different economic sectors as well as macroeconomic performance metrics, bottom-up models usually focus on one specific sector exclusively (e.g. the energy sector) and therefore use highly disaggregated data to describe energy technologies and end-use behaviour in greater detail. Hourcade et al.

(1996) summarises (in the context of mitigation cost studies) that existing bottom-up and top-down modelling approaches are primarily meaningful at the margin of a given development pathway. Therefore their application is valid under the following conditions: (1) Top-down models are valid "as long as historical development patterns and relationships among key underlying variables hold constant for the projection period" (Hourcade et al., 1996, 281) while (2) bottom-up models are valid "if there are no important feedbacks between the structural evolution of a particular sector in a mitigation strategy and the overall development pattern" (Hourcade et al., 1996, 281).

While historically the distinction between bottom-up and top-down energy-economic models has provided the framework for the contemporary modelling debate, there have been first attempts to develop "hybrid" models, merging the benefits of both analytical approaches (Hourcade et al., 2006; Jochem et al., 2007; Schade et al., 2009; Catenazzi, 2009). For example a more detailed representation of different electricity generation technologies has been integrated in top-down economic models (Böhringer and Rutherford, 2008; Steininger and Voraberger, 2003).

2.3 The model structure: modelled mechanisms and external assumptions

Different research questions are addressed by different models, capturing only those mechanisms of the real world that are relevant to answer the stated question (i.e. to serve their purpose). Therefore another basis for the distinction of different modelling approaches is the nature of the model itself or, more precisely, the assumptions and mechanisms embedded in the mathematical structure of the model. Hourcarde et al. (1996) distinguish between four major dimensions to characterise structural differences of existing energy-economic models.

The first structural characteristic relates to the degree of endogenization, the extent to which behavioural assumptions and mechanisms are endogenized in the model equations so as to minimize the number of exogenous parameters. The more behavioural assumptions and mechanisms a model internalizes, the better it is suited to predict actual outcomes. Those models that are externalizing most mechanisms are, on the other hand, more suited to simulate the effects of changes in historical patterns (Hourcade et al., 1996).

The second structural characteristic describes the extent to which non energy sector components of the economy or the environment are considered. The more detailed a model describes these mechanisms, the better it is suited for the analysis of wider economic effects of energy policy measures. A huge variety of models designed to serve different purposes can be found, which endogenize very different assumptions or mechanisms, such as economic, behavioural, engineering, geophysics or earth science mechanisms. There are also models capturing not only one of these mechanisms but a portfolio of them. The question of modelled mechanisms closely relates to the choice of the analytical framework, as for example IAMs aim to include as many mechanisms as possible, and – at least in their current state – are, however, subject to severe drawbacks as well (e.g. highly uncertain damage functions; see e.g. Pindyck and Wang, 2013; Pindyck, 2013).

Many state of the art economic models only capture a limited amount of economic and other mechanisms explicitly. In CGE models for example the sole mechanism that leads to the new equilibrium after an exogenous shock is the relative price mechanism. Many other mechanisms capturing behavioural, political, social, technological elements are neglected. Hence, the potential real world implications derived from results of such modelling exercises have to be critically reflected and complemented by other modelling techniques to eventually derive a more comprehensive and holistic picture. With respect to the analysis of long run low carbon transition pathways, there is increasing concern regarding the applicability of traditional economic models rooted in neoclassical economic theory, as some main modelling characteristics and implicit mechanisms are questioned: the relevance of prices, the implicit behavioural assumptions, the dynamics of technologies, the emphasis on flows over stocks.

The third and fourth structural characteristics refer to the extent of description of energy end uses and energy supply technologies, respectively. Models that describe end uses in more detail are more suitable for the analysis of energy efficiency measures, while models that focus on internalization of energy supply technologies are more suitable for the analysis of technological potentials (Hourcade et al., 1996).

Moreover, the various model specifications have to be checked whether they are able to separate the description of the structure – e.g. the elements of an energy system – from the mechanisms that are generating these structures. This is a major problem with neoclassical specifications since they intimately link structures and mechanisms. Similar problems might occur with system dynamic (SD) and agent based modelling (ABM) type specifications.

Every type of model is relying on exogenously given parameter values and assumptions regarding interdependencies within the scope of parameters and variables which are in turn triggering endogenous responses within the model. A crucial task in modelling is to decide whether a model element is determined endogenously or exogenously, depending on the underlying question to be answered. In CGE models, for example, modelers have to choose between certain variants of economic model "closures" (savings-investment, government budget, external balance). Furthermore, while some economic models such as CGE or IO models assume certain behavioural characteristics of agents (e.g. utility and profit maximization, representative agents) other approaches (ABM or SD) set out to endogenously derive behavioural details related to the emergence of complex phenomena.

2.4 The time horizon

Modelers have to be clear about the time horizon underlying their analyses, as different economic, social and environmental processes may behave differently or become relevant at different time scales. Hence the time horizon eventually affects the choice of the specific modelling methodology (see the following section), as long run analyses may assume economic equilibrium in which all markets clear and all resources are fully allocated, while short-run models need to incorporate transition dynamics and situations of disequilibrium (at least in some markets, e.g. unemployment). With respect to the definition of different time horizons, no standard procedure exists. However, short term is often assumed to reflect periods of five years or less, the medium term to range between 3 and 15 years and the long term to start at 10 years and beyond.

2.5 The underlying methodology

For energy and emissions related analyses the following methodological approaches have been employed, and are thus discussed in detail in section 3 below:

- Econometric Models
- Macroeconomic (Post-Keynesian) Input-Output Models
- Neoclassical Economic Equilibrium Models
- System Dynamics and Simulation Models
- Backcasting Models
- Optimization Models
- Partial Equilibrium Models
- Multi agent or Agent Based Models (ABM)

Optimization versus simulation

One aspect relevant across the above methodological approaches is the issue of optimization versus simulation. Building a model aims to serve a general purpose (prediction, exploration, backcasting) and to answer a more specific question of interest, all within a specific time horizon. The character of this stated question then determines the methodology eventually employed in the modelling exercise. Basically there are two different kinds of questions which are commonly stated by economic modelers: The first one is about the right choice in certain situations of interest; this demands optimization models. The second question scientists often ask is "what if…?"; this demands simulation models.

For example, CGE analysis is a mix of both: Mathematically, a CGE model solves an optimization problem; however, by changing input parameters the optimization routine gives different outcomes which can also be interpreted as simulations. Other types of models, such as ABMs and SD models do not optimize target functions with respect to certain constraints but simulate in a dynamic way the actions and interactions of either multiple autonomous agents or more aggregated system elements in an attempt to re-create and/or predict the appearance of complex phenomena.

For our field of analysis, i.e. in the context of transitions and a very-long run perspective, however, optimization per se is highly questionable for many reasons, among them ethical and uncertainty about technological developments.

2.6 The treatment of path dynamics (comparative static VS dynamic ("path explicit"))

Analysing the long-term transformation process to a low carbon society can be based on different modelling frameworks that differ with respect to their treatment of time and their explicit representation of transition paths. **Comparative static** models compare different states of system variables without taking into account the development between these states (for example GDP before and after policy interventions). Many economic models, such as static Input-Output and static Computable General Equilibrium (CGE) models are characterised like this. When developments over time are analysed with this kind of models, modelers often interpolate between different points in time to generate a hypothetical development path, however whether the development really follows this interpolated trajectory is not at the core of interest of such modelling approaches.

The counterpart to comparative static analysis is **dynamic** analysis, describing and investigating explicitly the path between different states of system variables. In the context of models that are rooted in neoclassical theory, development over time can be analysed either by **discretely** taking over values of system variables from one point in time to the next (e.g. "recursive dynamic" models, optimizing only within each period, but thereby implicitly also determining the intertemporal development), or by **continuously (fully dynamic)** optimizing intertemporal functions; for example maximizing discounted utility over the full time horizon at any point in time. Both versions of dynamic economic models have their drawbacks. On the one hand discrete dynamic models are nothing more than static models solved iteratively and their results dependent on exogenous assumptions (e.g. the interest rate), on the other hand fully dynamic CGE models assume perfect foresight and perfectly informed decision makers – assumptions that are not readily comparable with real world behaviour of economic agents.

To account for and simulate the real world, dynamic actions and interactions of different autonomous agents and their emergent effects on the system as a whole in the context of a transition to a low carbon society, the employment of agent based models (ABM) might be suitable.

While ABM focus on individual behaviour, actions and interactions, system dynamic (SD) models try to give an understanding of the behaviour of complex systems over time at a more aggregate level (i.e. by not explicitly distinguishing between autonomous individuals). The merit and main difference of SD models from other models studying the dynamic behaviour of complex systems over time is its use of internal feedback loops, the stocks and flows concept, and time delays that affect the behaviour of the entire system.

Furthermore, ABM and SD models – as well as any other non-stochastic model specification – allow for the introduction of randomness, uncertainty and emergent characteristics by e.g. using Monte Carlo Methods.

2.7 Regional and sectoral coverage, data requirements

The regional/geographical and the sectoral coverage reflect the level of detail at which the analysis takes place. The level of detail is an important factor linked to the structure of the model, as it determines which economic mechanisms and elements are endogenized in the model and which are treated as exogenous assumptions. Models at a global scale set out to explicitly model the global economy characterised by explicit market relationships. Regional models, most often referring to international regions such as the European Union or Southeast Asia, and local models focusing on subnational regions (such as Styria in an Austrian context), treat world market conditions as external assumptions.

Likewise to the geographical scope of a modelling framework, energy-economic models differ with respect to the explicit representation of individual economic sectors. Encompassing a high number of sectors within a country – or focusing on the most relevant, major economic sectors – allows for a comprehensive analysis of the most important cross-sectoral feedback effects and interrelations.

3 Methodological Approaches

3.1 Econometric methods in energy modelling

Energy systems are undergoing fundamental changes, driven by disruptions in technologies, markets and policy designs. Econometric methods have a long tradition in accompanying modelling and analyses of energy systems. We evaluate econometric practices with respect to their adequacy in dealing with long-term transformations of energy systems.

The method

A simple econometric specification for the demand of energy

Mainstream approaches to determining the demand for an energy flow *e* typically postulate the relationship

$$(1) \qquad e = e(q, p, x, z)$$

with the causal variables *q* for an economic activity, *p* for a (real) energy price, x for other variables (e.g. a weather variable) and z for an autonomous technical change.

Assuming a sample of time series, a general econometric specification of this relationship might be the following linear relationship

$$(2) \qquad a(L)e_t = b(L)q_t + c(L)p_t + d(L)x_t + z.t + u_t$$

which exhibits lag distributions, a linear trend component and a stochastic error term u_t. Typically the variables are transformed into logarithms, thus obtaining elasticities for the estimated parameters.

This modelling approach faces a number of limits. The number of parameters to be estimated, in particular those for the lag distributions, require a long sample range which in turn may violate the underlying model specification of an invariant structure. Furthermore this model specification is not able to deal with interfuel substitution, i.e. switching the energy mix.

These limits lead to extended model specifications which include on the one hand additional data by using also cross-section information (panel data) and on the other hand additional restrictions on the parameters of the general specification (2).

Dealing with interfuel substitution

Demand for energy obviously needs to be considered in the context of an energy mix which in turn stimulates research for explaining the causalities for the composition of the bundle of energy consumed by households or needed in the production of goods. For modelling this interfuel substitution basically two approaches have emerged.

The Almost Ideal Demand Systems (AIDS) results from a consumer demand model that partition total expenditures (i.e. for energy) for a bundle of goods (i.e. different fuels) according to the prices of the individual goods (i.e. fuel prices).

A production-based approach explains energy as the output of several factors (i.e. fuels). A further extension includes non-energy inputs, as the capital, labour and materials in a KLEM model. In a so-called translog specification the main drivers for these models are relative energy and relative factor prices.

The econometric implementation of these modelling approaches suffer most often from rather unreliable time series on factor prices and energy prices, a deficiency that is echoed in the rather weak significance of estimated direct and cross price elasticities.

Modelling integration, co-integration and Granger causality

A very different modelling paradigm has emerged over the last three decades in the context of non-stationary stochastic processes. Accordingly economic variables as GDP and energy are investigated with respect to their individual long-term behaviour (typically exponential trends before the economic crisis that started in 2008) and thus classified by what is called the degree of integration. In a next step joint relationships of variables are investigate under the heading of co-integration. Finally statements are made, if one variable improves the prediction of another variable and this is termed Granger causality.

It seems to be fair to say that these modelling approaches just reflect the application of econometric methodology that has become available to energy data without reflecting if this methodology is adequate to the issued to be dealt with. The exponential trends of the past seem to be gone, a fixed long-term relationship, even of a stochastic type, is rather not desirably if we postulate this for an energy flow and an economic activity. Finally predictability should not be prematurely mixed with causality in the sense of cause and impact.

Representative econometric models for the energy system of an economy

A typical representative model with a global coverage is E3ME, a macro-econometric E3 (Energy-Environment-Economy) model. Models like E3ME claim as a distinctive feature their treatment of resource use, including energy, and the related greenhouse gas emissions embedded into sectoral economic framework.

Despite the merits of such an integration many deficiencies as to the treatment of energy remain that are crucial for obtaining a better understanding of long-run transition processes. These shortcomings concern the rather simplistic treatment of technological progress, the overstated role of prices as drivers for structural changes, and the limited treatment of the cascade structure of the energy system.

Some conclusions for long-term transition analyses

In view of the usability of econometric models for obtaining a better understanding of the long-term transition options in an energy system, the conclusions are rather sobering.

Almost all econometric specifications include market driven behavioural assumptions, visible in the role of energy prices in the model specifications. The specifications are therefore hardly able to deal with non-price determined mechanisms that are representative in particular in the context of innovation policies. The estimated elasticities for prices and activities have very limited credibility because of the inherent conflict between the required long time series from a statistical point of view and the accompanying structural changes that violate the statistical model assumption of structural invariance. Most econometric analyses of the energy system just ignore this issue by not reporting the sensitivity of their estimates with respect to variations in the sample size and in the specifications.

Other deficiencies are even more fundamental, as the almost complete absence of details in the energy cascade, in particular the central role of functionalities that are provided by the interaction of energy flows and corresponding stock variables. This extended view of an energy system emerges, however, as a prerequisite for understanding the subtleties of long-term transformation processes.

3.2 Dynamic New Keynesian Input-Output Models

The method

One of the model classes that aim at introducing innovative modelling techniques are New Keynesian models. They are developed in the tradition of general equilibrium models in the sense that their long run equilibrium results from market clearing prices. As CGE models and many macroeconometric models, New Keynesian Models build on an input output structure displaying the interlinkages between sectors.

In the short run, institutional rigidities and constraints, such as wage bargaining or liquidity constraints, imply a deviation from the long run equilibrium path.

New Keynesian Models are inter alia applied to address the critical role of environmental and resource constraints for economic development (Jackson et al., 2014). The model structure and the underlying assumptions are suited to illustrate the impacts of the demand for goods and services on energy and resource use or on emissions.

Typical building blocks of a New Keynesian Model

The typical building blocks of a New Keynesian Model comprise the household sector, the production sector, labour market and the government sector. In the short run the demand driven model shows deviations from the long run equilibrium stemming from liquidity constraints or other rigidities. The adjustment paths to the long run equilibrium solutions can be modelled in different level of detail for the different building blocks of the model. In the long run, adjustments in the wage rate determine the full employment equilibrium in the labour market, which in turn determines household income and respectively consumption.

Models that integrate environmental aspects typically treat energy demand as a separate category of non-durable commodities, differentiating between different fuel types. In the long run, demand for different fuel types is determined by (equilibrium) income, autonomous technical change and fuel prices.

Energy demand in the WIFO DYNK model

The DYNK model by WIFO (Kratena and Sommer, 2014) treats energy use in a detailed way. In the household sector, an innovative approach for modelling energy demand is used: Starting point is energy service demand which is the result of the energy efficiency of the capital stock and final energy demand by fuel type. This approach explicitly illustrates the role of stock-flow interactions in the provision and demand of energy services. Household energy service demand is determined by the energy service price, as a function of the energy price and the energy efficiency parameter. In the short run, liquidity constraints and a fixed capital stock – reflected in a given efficiency parameter – imply that energy service demand is determined by changes in the energy price. In the long run, changes in energy prices induce adjustments of the capital stock that can result in changes in the energy efficiency parameter and thereby affect the energy service price.

In the production sector, the input factors capital (K), labour (L), energy (E), imported non-energy materials (M^m) and domestic non-energy materials (M^d) are differentiated. The shares of the different input factors in production are determined using a translog specification based on factor prices. In a second step, the shares of the different fuel types are estimated, also based on a translog function. Technological change is modelled via autonomous technological change, for the different input factors as well as in form of total factor productivity.

Some aspects for long run transition

With respect to gaining insights into long term transformation processes a number of fundamental uncertainties with respect to the development of economic activities and prices and the convergence to an equilibrium solution remain. The model solutions depend strongly on the development of (relative) prices that drives changes in the economy.

As in most economic model classes, in New Keynesian Models long run development is implemented as an extrapolation of trends observed in the past. Technological change is modelled as incremental technical change; radical technological change cannot be captured in such models. When used for policy evaluation it is the underlying set of uncertain assumptions in the reference case that mainly determines the effects of policy shocks. The decisive role of prices for model solutions typically constrains the simulation of policy alternatives to price instruments like taxes.

The merit of the WIFO DYNK model is that it illustrates the interaction of stocks and flows for energy services. What drives the demand for energy services, however, is exclusively driven by prices.

3.3 Optimization Models

The method

An optimization approach aims for the minimization (e.g. costs, CO_2-emissions) or maximization (e.g. profits) of an objective function. The results of such models are solutions found by the "solver"-algorithm which are considered as optimal (or close to the optimum) with respect to the objective (or target) function. Therefore optimization models are prescriptive rather than descriptive. This means that this approach can rather be used for "*how to*" instead of "*what if*" research questions (Ravindranath et al., 2007).

Optimization models usually constitute from at least two parts: The first part is the modelling environment used for the model formulation and model building. Most optimization models are written in high-level, functional programming language in a declarative way. The computation is then done by evaluating the mathematical expressions. Commonly used optimization program languages are GAMS, MPL, AMPL, AIMMS or MOSL. In a subsequent step, the modelling environment translates the source code into equation system. The "solver"-software forms the second part of the model, which derives the solution by solving the equation system and thus evaluation the optimality of solutions simultaneously. For several widely applied (bottom-up) optimization models (e.g. MARKAL, TIMES, MESSAGE, OSeMOSYS) a third component, the model-builder-toolbox using a graphical user interface (GUI) exists (e.g. Excel-file in case of the OSeMOSYS). This has the advantage that model-building can be done more easily as the developer doesn't need to write source-code. However it is also limited to the model capabilities as defined by the GUI.

Although most optimization models follow this pathway, this is not necessity. Also a procedural model definition can be applied. An example for a procedural model approach is the

REMod (Renewable Energy Model) developed by the Fraunhofer ISE institute. The model itself is written in a Pascal-derivate, some sort of solver is applied which then identifies a (close-to-)optimal solution by consecutively evaluation the optimality of different solutions.

Optimization approaches are used for Top-down models (e.g. CGE (e.g**. GEM-E3 model)** or partial equilibrium models (e.g. (MARKAL-)MACRO) as well as Bottom-up (technology explicit) models (e.g. MARKAL, MESSAGE or TIMES model).

The mathematical approach for solving

Van Beeck's (2009) fifth dimension, the **mathematical approach,** defines how optimization models solve the problem. Most energy related bottom-up optimization models use common mathematical methods such as Mixed Integer Linear Programming (MILP), partly Multi-Objective Linear Programming (MOLP). If the model optimizes the path from an existing system towards the optimal system state, also Dynamic Programming (DP) methods are to derive their solutions. Top-Down optimization models and some (bottom-up) energy models use more advanced methods such as Non-Linear Programming (NLP), Mixed Integer Non-Linear Programming (MINLP), and (Multi-Objective) Fuzzy (Linear) Programming ((MO)F(L)P). The Fuzzy Logic approach (or Fuzzy Programming, FP) constitutes an improvement with respect to penny switching behaviour. Similar (in a non-mathematical definition) to the logit model and other probability approaches commonly used in discrete choice analysis, Fuzzy Logic allows that a variable is "partly true" and defines "*how much*" a variable is a member of a set. Thus, Fuzzy Logic approaches are more suitable to find realistic solutions for decentralised optimization problems with a medium or high degree of uncertainty than conventional approaches (Zimmermann, 1978; Jana and Chattopadhyay, 2004).

Strengths

The main advantage of optimization models is that they inherently consider the optimality of a solution (as measured by the objective function). Therefore this kind of models automatically rules out less preferable solutions.

Weaknesses

The solver-software, responsible for finding the (close-to-)optimal solutions needs to evaluate a large number of systems states with respect to status concerning the objective function and the model constrains. Therefore such models are limited to a restricted complexity and/or simplifications, in order to find a (close-to-)optimal solution within a reasonable time. With respect to complexity and simplifications, linear models (linear programming) define one end of the spectrum. Modern computers are easily able to solve such systems with millions of equations, however the restriction to linear systems makes this kind of model formulation basically unusable for real-life research questions. A less restricted formulation are Mixed-Integer-Linear-Programs (MILP) that allow variables not just to be an element of rational numbers but also of a restricted set of integers. Again such models can be solved for very large number of equations and variables within a reasonable time (days?) if the model is defined carefully. Yet, integrating part load behaviour into such a structure already requires substantial modelling in order to keep the model (easily) solvable. Most bottom-up energy-system models apply the MILP approach. On the other end of the spectrum range Non-Linear Programming (NLP), Mixed Integer Non-Linear Programming (MINLP) which are much harder to solve. This is especially the case for models with positive feedback loops (concave models). NLP or MINLP therefore require that the defined model has a low degree of complexity.

Another disadvantage of (commonly solved) optimization models is their behaviour with respect to inferior technologies. Usually the degree to which a given technology is part of the solution depends only on superior technologies and their restrictions as well as their own restrictions, while it is independent from inferior technologies (penny switching behaviour). This is probably the main reason for the commonly held position that conventional optimization techniques, are not particularly suited to analyse systems where many individual decision-makers decide on many rather small subjects. This “penny switching behaviour” is not necessarily given and could be avoided in principal – at the cost of increased computational time. Yet most applied energy systems optimization models accept such a behaviour in order to keep the model reasonable solvable.

Representative optimization models for the energy system of an economy

The MARKAL (MARKet ALlocation) model, its successor the TIMES (*The Integrated MARKAL-EFOM System*) model, the MESSAGE model (*Model for Energy Supply Systems And their General Environmental impact*), and the OSeMOSYS (*Open Source Energy Modelling System*) are well-known and widely applied energy system optimization models (Pfenninger et al., 2014).

Some conclusions for long-term transition analyses

Optimization models are well suited and widely applied to describe solutions for a “technological-optimal” hypothetical target system in a distant future as well as the “technologically optimal” pathway towards such a system. They are however less suited to evaluate realistic forecasts for systems stages which are far from the optimal solution as defined by the objective function, which is usually the case for real-life systems. They are furthermore not particularly suited to evaluate the real-life effects of policy measures or other framework conditions for complex energy systems.

3.4 Neoclassical Computable General Equilibrium (CGE) models (top-down optimization)

The method

Typically, a computable general equilibrium (CGE) model depicts the economy as a closed system of monetary flows across production sectors and demand agents on a yearly basis. These flows are based on real-world national input output tables as well as additional accounting data and are combined with the general equilibrium structure developed by Arrow and Debreu. Accordingly, CGE models solve numerically to find a combination of supply and demand quantities as well as (relative) prices in order to clear all of the specified commodity and factor markets simultaneously (Walras' law).

The basic underlying mechanisms are that producers minimize their production costs (or maximize profits) subject to technological constraints (production functions), whereas consumers maximize their consumption (or "welfare") subject to given resource and budget constraints (factor endowments and consumption functions).

Once the model is calibrated to a "benchmark" equilibrium of a certain base year it is shocked exogenously, triggering adjustments in supplied and demanded quantities and thus relative prices until all markets are in equilibrium again. The emerging new equilibrium depicts the state of the economy after the shock (i.e. shows how the economy would look like, if a certain policy had been introduced) and is compared to the benchmark equilibrium to analyse changes in endogenous variables such as activity levels of sectors and consumption, relative prices or welfare.

Mathematically CGE models are optimization problems since producers and consumers maximize/minimize their objective functions; however the use of CGE models is more of simulation character, as typically different counterfactuals are used in economic impact analysis, leading to different solutions of the models' optimizations routine, which then are interpreted as different results of simulation scenarios.

Strengths

The main advantage of CGE models is their ability to capture interlinkages across all economic sectors and agents. This means that "indirect" or "knock-on" effects of e.g. the introduction of an energy tax can be quantified, giving a broader picture than an isolated sectoral analysis.

Since the effects to the whole economy are captured by CGE models, the effects on typical macro indicators, such as GDP, national consumption or welfare and tax income, can be analysed. These changes in macro indicators then may be decomposed into different parts, e.g. the different contributions of sectors of interest to the change of GDP, which makes this approach very attractive.

Weaknesses

Next to the strengths of the CGE approach there are also limitations and weaknesses. In general the underlying neoclassical theory of general equilibrium is subject to heavy critique. However, the aim of the underlying paper is to analyse the ability of different methodological approaches in the specific context of energy-transition, hence we do not further address this very general discussion of general equilibrium theory.

A fundamental weakness in the CGE method is that only annual monetary flows are modelled explicitly. Capital stocks, such as buildings or power plants, are not captured, despite their importance in energy-transition modelling.

Another drawback of CGE models is that they are often too aggregate and coarse with respect to technological detail. Many CGE models use sector aggregates such as the energy sector, which includes generation and distribution of all kinds of energy. The supply side of these aggregates is typically modelled as constant elasticity of substitution (CES) production functions, which combines different production inputs such as primary factors (capital, labour, resources) and intermediate inputs (material and services) to generate output. Since the different inputs are partly allowed to substitute each other, elasticities of substitution are necessary. These elasticities usually stem from regression analysis based on historical time series, leading to the problem that there is no guarantee that they will not change in the future (Grubb et al., 2002).

When analysing energy transition pathways it is crucial to model different technologies separately, since their production structures may differ fundamentally. Even if different technologies are modelled separately in CGE models (such as in top-down bottom-up hybrid models as in Fortes et al., 2014) the problem remains that no radical changes are possible endogenously within the model framework since the production functions do not change over time. Regarding technological change usually factor productivity improvements are applied, however using this method radical changes or the emergence of fundamentally new technologies are not possible. Next to supply side issues, there are also weaknesses regarding the demand side. More precisely, substitution possibilities in final and intermediate demand are of crucial importance, requiring again elasticities of substitution.

Representative CGE models for the energy system of an economy

Typical CGE models which focus on energy-economy-environment interaction are the GEM-E3 model (General Equilibrium Model for Energy-Economy-Environment interactions) for the European Union (Capros et al, 2013a) and PACE (Policy Analysis based on Computable Equilibrium; Löschel, 2015).

GEM-E3 focuses on the European Union and is of recursive dynamic type, solving in 5-year steps until 2050. It is mainly used to assess climate and environmental policy, hence including primary energy sources and energy technologies. PACE is a similar model, however static comparative.

Some conclusions for long-term transition analyses

A first conclusion to be drawn for long-term transition analysis using CGE models is that the underlying fundamental mechanism of optimization of producers and consumers – assuming perfect information and rational behaviour solely based on prices – is unrealistic, leading to unrealistic results. Many other factors than just prices determine the actual behaviour of agents, hence in that regard CGE models are too short sighted.

The basic emission reduction mechanisms in CGE models are the following (cf. Capros et al., 2014): (i) substitution processes between fossil fuel inputs and non-fossil inputs, (ii) emission reductions due to a decline in economic (sectoral) activity and (iii) purchasing abatement equipment. However, CGE models do not allow for radical endogenously changes in the energy system (bifurcation points) which are necessary for deep decarbonization, since production and consumption functions are determined ex ante and do not change over time. Technological change thus only happens at the margin via price induced factor substitution (endogenously), productivity growth and autonomous energy efficiency improvements (both exogenously) (cf. Böhringer and Löschel, 2004).

Despite these drawbacks CGE modelling may offer also opportunities to capture the indirect effects of certain policy interventions or technological change can be provided to shock the model exogenously (on the premises of having enough data on possible future developments regarding energy technologies and energy demand available). These indirect effects are of crucial importance, as sectoral models which do not take into account a macro-economic embedding may under- or overestimate effects.

3.5 Partial Equilibrium Models (bottom-up optimization)

The method

The basic concept of equilibrium models is to determine the state where demand and supply of different commodities are equal (equilibrium price) and thus market clearance is achieved. Partial equilibrium models only consider a specific market or sector where the economic equilibrium is determined independently from prices, supply and demand from other markets. Therefore other markets and sectors are considered to be fixed, not considering possible interrelations. Thus all parameters not incorporated directly within the model have to be provided exogenously.

The advantage of partial equilibrium modes is that they are capable of describing specific markets more detailed and disaggregated. This is also beneficial for analysing the effects of different policies.

Representative Models

Since partial equilibrium models are only capable of a single (or limited amount) market or sector they consider specific problems. Prominent examples for partial equilibrium models are PRIMES and CAPRI. PRIMES is an energy model to calculate developments on the energy market (for details see also chapter 4.2). CAPRI is a model for the agricultural sector used for the assessment of agricultural and trade policies with a focus on the EU (CAPRI 2015). Both models are extensively used be the European Commission.

Some conclusions for long-term transition analyses

Some models like PRIMES have been extensively used to describe long term transitions (Capros et al., 2013b). A possible drawback is that those models rely on exogenous parameters (e.g. world market prices for fossil fuels, CO_2 permit prices) and neither provide direct feedback nor consider interrelationship to the sectors and markets exogenously provided. This may have considerable drawbacks on the long run, e.g. significant changes in energy market may have a considerable impact to the whole economy.

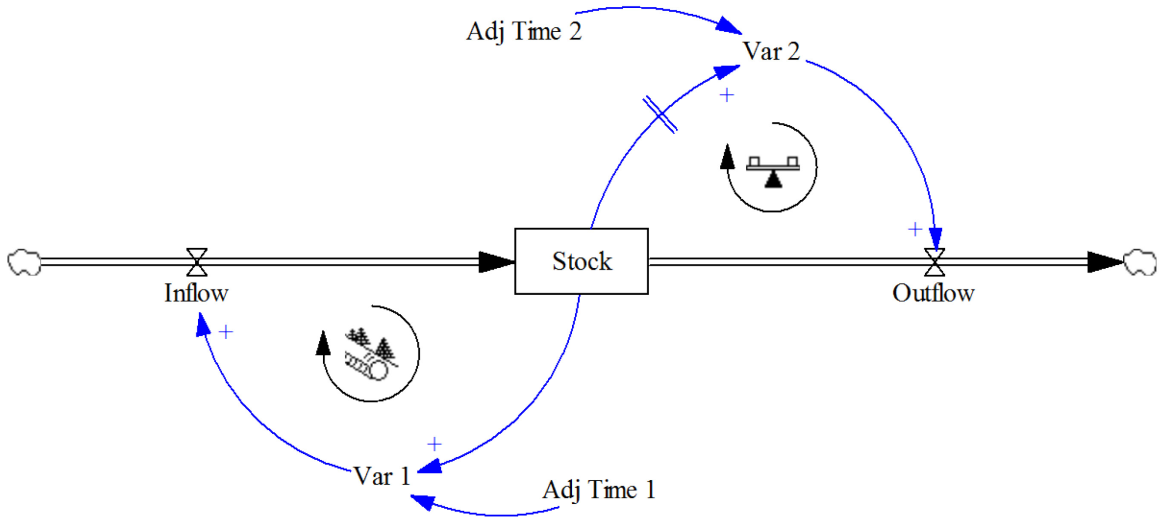
3.6 System Dynamics and Simulation Models

The method

The concepts of system dynamics was developed by Jay W. Forrester in the late fifties with the aim to asses and improve industrial processes. System dynamics models allow in a very intuitive way to model, simulate and analyse complex dynamic problems. The basis of a system dynamics model is a system of differential equations which are numerically solved in a sequence of time steps. Characteristic to system dynamics is the incorporation of complex feedback structures within the different system variables. Thus they are simulation but not optimization models.

The two central concepts of system dynamics are stock and flows in combination with the generated feedback and interrelations. A general stock and flow diagram is shown in Figure 1. The 'stock', which is visualised by the rectangle, contains the current level of an entity (e.g. price, demand). This level is increased and decreased by 'flows' connected to the stock. These flows are illustrated in Figure 1 by the thick arrows with the 'valve' symbol. These flows are influenced by different parameters, variables and stocks generating complex feedback loops.

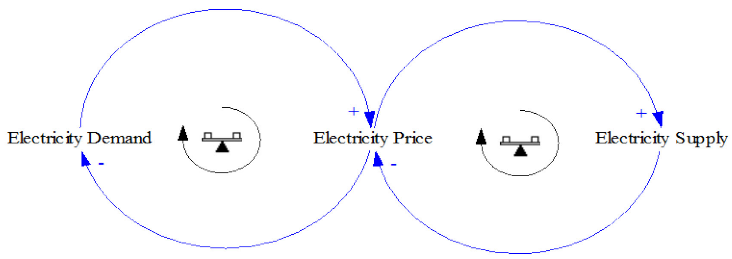
Figure 1 General example of stock and flows within the system dynamics approach.



The level of the stock, which is indicated by the rectangle, is altered by the flows ('Inflow', 'Outflow'). The blue arrows indicate the influence of parameters, variables and the stock on the different flows. The feedback loop 'Inflow', 'Stock' and 'Var 1' generate a reinforcement (indicated by the sledge) whereas the feedback loop 'Stock', 'Var 2' and 'Outflow' result in a balancing situation (indicated by the scales). The double stroke on the arrow from 'Stock' to 'Var 2' indicates a time delay until the feedback from the stock shows effects von 'Var 2' (Dykes 2010).

Besides the possibility to simulate the effects of the different interrelationships within the model it also provides a convenient way to analyse the driving forces within the system. In Figure 2 a simple example of feedback loops are illustrated. Feedback loops result either in reinforcement or in balancing (in Figure two balancing feedback loops are shown).

Figure 2 Simple example of feedback loops in an energy system.



On the left an increase of the electricity demand results in a higher price which results in a decrease of the demand (balancing; indicated by the scales). On the right an increase of the electricity price results in an increased supply of electricity which induces a decrease of the price (balancing)(Dykes 2010).

Besides the capability to describe dynamic and complex problems appropriate system dynamics model are increasingly combined with other methods like generic algorithms, iterative algorithms and game theoretical approaches. Also stochastic approaches, like Monte Carlo simulation, may be implemented (Teufel et al., 2013).

Representative models

Regarding the energy market a number of system dynamics models have been developed and successfully applied (Teufel et al., 2013). An example would be the model Kraftsim (Vogstad 2004) used for investigating the Nordic electricity market and simulating the effects on greenhouse gases caused by different policies. A more comprehensive overview can be found in Teufel et al. (2013).

Some conclusions for long-term transition analyses

Available system dynamics models have shown to be capable of describing energy and power systems adequately, including transformation processes until 2050. The incorporated consideration of interrelations may be an advantage for describing long run transformation processes.

However as this approach is a simulation and not an optimization method it may be appropriate to simulate complex problems but it lacks the possibility to find optimal pathways (e.g. least costs) for the transition. Regarding this aspect the combination with other methods may be a possible approach.

3.7 Backcasting Models

The backcasting[1] approach was developed in the 1970s by Amory Lovins for the analysis of energy systems. Backcasting is seen as an alternative to conventional energy forecasting approaches that estimate a continuous and substantial increase in energy demand. Since the 1970s the approach has been frequently applied in energy studies as well as in studies dealing with sustainable development in general.

In contrast to forecasting models that are usually based on past trends, backcasting approaches start from a normative vision for a desirable future, such as a low carbon society with a reduction of GHG emissions by 80-90% by mid century compared to 1990. From that vision of the future, a development path is traced back to the current situation. Backcasting is hence well suited for modelling complex issues such as a transformation towards sustainable consumption and production patterns. Furthermore, the approach allows for modelling structural breaks that cannot be captured with traditional forecasting approaches. This is a valuable feature for modelling the very long-run, as a mere continuation of past trends over the next decades is very unlikely.

[1] The term 'backcasting' was introduced by Robins (1982), while Lovins initially used the term 'backwards-looking analysis' (Quist, 2007).

Backcasting is frequently used for (more or less) qualitative descriptions of the future (see e.g. Wächter et al. 2012 for Austria). In their energy perspectives for Austria, Köppl and Schleicher (2014a, b) use the quantitative backcasting model sGAIN for analysing low carbon energy structures in Austria for 2030 and 2050.

The WIFO sGAIN modelling framework

sGAIN by WIFO represents a detailed bottom up model of the energy system. In Köppl and Schleicher (2014a,b) the model is used for backcasting, using the EU 2050 Roadmap as normative vision for 2050. The modelling framework puts energy services into the center of the analysis of energy structures that are compatible with long term low carbon targets. Data for energy services are typically not available. Information from useful energy balances are used to demonstrate quantity and quality of energy used for the provision of energy services. The model structure details useful energy categories by sector and energy source and puts a strong emphasis on innovation and energy productivity at all levels of the energy chain including the supply side. Various combinations of changes in the demand for energy services and energy productivity that achieve the same output in terms of energy flows and emissions are displayed.

Some aspects for long run transition

Relevant for long run transitions is the ability to capture structural breaks that are necessary for a fundamental transformation of existing energy systems. This applies also to a clearer depiction of specific technologies and thus comes closer to include more radical technological change. Backcasting requires the definition of explicit target values that need to be thoroughly chosen and argued. The same holds true for modelling of the paths between the future vision and the current situation.

3.8 Multi Agent or Agent Based Models (ABM)

The method

The approach of ABM is a very general one as it can be used to model nearly any system in dependency of the purpose of the model. The variety of application ranges from physical over biological to social systems, while the approach is often seen in contrast to Equation Based Modelling (EBM) or System Dynamics, which have a similar general applicability. In a strict technical perspective, there is no difference between ABM and EBM as any ABM can be also expressed by an explicit set of mathematical formulas used by EBM (Epstein, 2006, p.xiv, p.27). However, in practice this set of formulas would be of hardly manageable size and complexity. The specifics of ABM, constituting a manageable modelling framework and distinguishing them from other modelling approaches, refer to 3 crucial points.

- The subjects of modelling are the system's individual components and their behaviour. The behaviour of the modelled agents depends on the local interaction with other system elements and individual optimization based on each agent's particular characteristic (as e.g. endowment, location or size).

- The possibility of (geographical) special representation of system elements. Agents do usually not interact with all possible system elements but only with those in their neighborhood. This specification can capture particularities for interaction including topological circumstance, transfer of information and network structures.
- The stochastic process of simulation. Other than deterministic approaches, in which the outcome of a model is fully determined by the parameter setting and the initial conditions, stochastic approaches as ABM bear an inherent randomness. Therefore one individual model simulation with a specific parameter setting and initial conditions can show only one possible outcome out of a well-defined function space, but not a general solution (Epstein, 2006, p.29).

As an implication of the first specific, a system behaviour may arise, which cannot be predicted from the behaviour of the individual agents, as it emerges from the adaptive interaction between the agents and their environment. In that way ABM are a Bottom-Up approach in which the autonomous behaviour of the agents determines the state of the system instead of a Top-Down approach (like System Dynamics, CGE,…) in which the state of the system is described only by variables. Further, an analysis of an ABM can be made not only on the aggregate system output but also on the agent level. However, an empirical ABM approach usually needs not only other/unconventional sources of data but also relies more heavily on more comprehensive data, specifying the multiple agents' particular characteristics.

Concerning the second specific, a large range of modelling possibilities becomes relative easily accessible. Models of social or economic systems in an agent based framework are only seldom restricted to *homo economicus* decision rules and can relax certain stringent conditions from neoclassical models, like perfect information, location or size of agents, while still yielding a fruitful analysis (cf. Epstein, 2006, p.xvif).

The third specific of a stochastic simulation is closer to processes in the natural world because of its inherent randomness. However, this has the price of stark increasing complexity of the model, demanding a comprehensive way of simulating and analysing the model. On the other hand, stochastics determine discrete decisions of agents and simulation in discrete time steps.

Strengths

- With ABM questions of emergence can be treated as the systems behaviour results of the interaction of its components. ABM can merge the micro with the macro perspective in that sense that well studied individual behaviour (as e.g. of plants, animals, people,…) can be modelled in one framework with changing system conditions – the state of system changes because of the individual behaviour and at the same time the individuals adapt their behaviour to the changes of the system.

- Within the approach of ABM uncertainties can be addressed because of the stochastic modelling character.
- ABM can handle also "nonequilibrium dynamics" – if equilibrium exists but is not attainable (e.g. on acceptable time scale) (cf. Epstein, p.xiii)

Weaknesses

- Additionally to mathematical and statistical modelling abilities, as necessary in other approaches (e.g. econometrics), also further modelling as well as programming and simulation skills are needed. This contains on the one hand the inclusion of different concepts as adaptive behaviour, interaction and emergence. And on the other hand, stochastics affords an iterative way for testing and analysing models.
- As already mentioned, data mining for empirical modelling with ABMs in social sciences is a big issue, as mostly micro data on an individual base for a large number of agents would be often required.

4 Identification and evaluation of existing "prototypical" models (selection)

For each of the model classes which we define by their underlying methodology, we select a "prototypical" model for further investigation. As a "prototypical" model we define a model which is prominently used in the analyses of energy-economic research questions either by the research community or by policy makers (such as the EU). These "prototypical" models have been classified by making use of the spreadsheet classification scheme developed in this WP on the basis of the previously described characteristics that are relevant for the suitability of energy-economic models for long term transition analyses.

4.1 Evaluation of specific "prototypical" models

PRIMES (Partial Equilibrium)

The *Price-Induced Market Equilibrium System* (PRIMES) is an energy system model to calculate projections of energy markets for the analysis of energy and climate policies in Europe. The model simulates the development of energy demand, energy supply and technology on the basis of market equilibrium (PRIMES 2014). Hence, PRIMES is a partial equilibrium model for the European energy system. Furthermore the model aims to represent agent behaviour within the multiple markets. This is achieved by a modular approach where each module represents a specific agent, either a demander or supplier of energy. The behaviour of the agents is modelled through a microeconomic foundation which maximises the benefit (profit, utility, etc.) of each representative agent. To combine the sub-models equilibrium prices in different markets and equilibrium volumes considering balancing and constraints are determined.

PRIMES provides detailed energy balances in line with Eurostat statistics including sectoral demand by fuel as well as the structure of the power system and other fuel supplies.

Moreover, energy prices and costs can be obtained such as costs per sector, investment costs, overall costs and consumer prices.

Since the economic development is modelled outside PRIMES there is no feedback generated by developments in the energy market. For the power system, daily and seasonal variations are modelled at an hourly resolution taking into account typical intra-day power load, wind velocity and solar irradiance. Despite this and detailed coverage of interconnecting capacities of electricity and gas flows, the model lacks information and representation at below-country levels such as retail infrastructure. This may be a particular concern if more volatile and decentralised production of electricity exceeds local grid capacities at short. Nevertheless, PRIMES should be well capable of simulating long term energy system transformation and restructuring up to 2050, both in the demand and the supply sides.

POLES (Simulation / System dynamics)

The POLES (Prospective Outlook on Long-term Energy Systems) model is a global energy supply, energy demand and energy prices forecasting model, developed within the VENSIM system-dynamics software package[2]. It has been developed by Enerdata and the CNRS National Center for Scientific Research.

It simulates the energy supply and demand (energy balances) of 15 economic sectors and of more than 57 countries and world regions within a partial equilibrium framework and explicitly considers about 50 energy supply technologies. The demand is modelled taking "into account the combination of price and revenue effects, techno-economic constraints and technological trends."[3] The simulation is done on a yearly basis.

POLES is a proprietary model, analyses with this model are rather provided as service by Enerdata; it is not (off-the-shelf) foreseen to hand-out the model to customers. Furthermore the included technologies are fixed and cannot be altered (by customers).

GEM-E3 (CGE)

The GEM-E3 model (General Equilibrium Model for Energy-Economy-Environment interactions) for the European Union has been applied for various climate and energy policy simulations to support decision makers within the European Commission. The main features are as follows (c.f. Capros et al, 2013a): (i) the model is of multi-country type with specific representation of all EU-15 member states, which are linked through endogenous bilateral trade, (ii) in every country multiple sectors and agents exist, allowing to analyse distributional effects and (iii) GEM-E3 is of recursive dynamic type, solving for general equilibrium in a specific year and then passing data on to the next year, for which a new equilibrium is solved. Furthermore the model includes taxes, subsidies and public spending (including deficit financing).

[2] http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php.

[3] http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php.

GEM-E3 is mainly used to assess climate and environmental policy (e.g. by Mayeres et al., 2008; Pan, 2005; Saveyn et al. 2011 or Jansen and Klaassen, 2000) and therefore special focus lies on the competition between the main power generation technologies (coal, oil, gas, nuclear, wind, biomass, solar, hydro, CCS coal and CCS gas) with the respective greenhouse gas emissions (see Capros et al., 2014 for more details). Recently, the model was also deployed to analyse macroeconomic climate change impacts (e.g. by Ciscar et al., 2012).

Regarding low carbon transition and pathway analysis GEM-E3 was linked to various bottom-up optimization model such as TIMES (e.g. by Fortes et al., 2013, 2014) to overcome the caveat of poor technological detail of the CGE model, but being able to quantify the macroeconomic implications of low carbon (policy) scenarios. Similar modelling practice was carried out by Koopmans and te Velde (2001), Kumbaroglu and Madlener (2003), Messner and Schrattenholzer (2000), Scaramucci et al. (2006) and Wing (2006). Such studies (integrating bottom-up and top-down models) may serve as a good starting point for a holistic integrated assessment of energy-economic low carbon transition analysis for Austria.

MARKAL / TIMES (Optimization)

MARKAL and TIMES are dynamic (path dependent) bottom-up optimization modelling toolboxes developed by the International Energy Agency (IEA) within the Energy Technology Systems Analysis Programme (ETSAP). MARKAL was developed in the mid 90s, TIMES in the early to mid 2000s. According to the MARKAL[4] homepage is now applied by more than 70 institutions in more than 35 countries.

MARKAL focuses on the energy sector only, the main purpose of MARKAL models is to identify and evaluate "target-oriented integrated energy analysis and planning" using a least cost approach. The MARKAL toolbox has been superseded by the TIMES (*The Integrated MARKAL-EFOM System) toolbox.* The main advantage of TIMES compared to MARKAL is its flexibility. It allows several interacting regions and to sub-divide the year into several user-defined time periods. Both toolboxes contain a partially equilibrium models for the energy sector (considering supply curves of and demand curves for energy carriers and the subsequently derived energy prices).

One of the main advantages of MARKAL and TIMES is that they are widely used in the energy system planning community and easy-to-use model building (less steep learning curve). A disadvantage is the still rather rigid structure. Furthermore, they do not optimize the electricity supply for medium- to long-term energy system planning, energy policy analysis, and scenario development with a large share of intermittent energy sources (e.g. wind and PV).

GAINS (Scenario analysis or optimization)

The *Greenhouse gas Air pollution Interaction and Synergies* (GAINS) model is an integrated assessment model which is based on a technology specific bottom-up approach. It derives

[4] http://www.iea-etsap.org/web/Markal.asp.

on the basis of emission factors and abatement effects the anthropogenic emissions, the resulting atmospheric pollution and impacts on human health and environment (Amann, 2012).

The GAINS model can be operated in a 'scenario analysis' and an 'optimisation' mode. In the 'scenario analysis' mode it analyses the pathway from the emitting source to the impact and allows therefore to assess the costs and benefits of different emission abatement strategies. In the 'optimisation' mode it derives the optimal combination of different abatement and mitigation options which achieve the best overall benefit at minimum costs.

To be able to calculate the emissions of different pollutants on the basis of activity data the GAINS model incorporates around 1000 types of emission sources which are specific regarding economic sector and country (Capros et al., 2013b).

In order to describe the different mitigation options and pathways GAINS considers around 1,500 end-of-pipe measures to assess the abatement of a wide range of different air pollutants including greenhouse gases. The different mitigation effects are derived on country and sector specific implementation costs. This allows a detailed assessment of the environmental impact of different policies and measures (Amann, 2012).

Since the different activity levels are exogenous the different costs of the abatement measures generate no feedback regarding the underlying economic models.

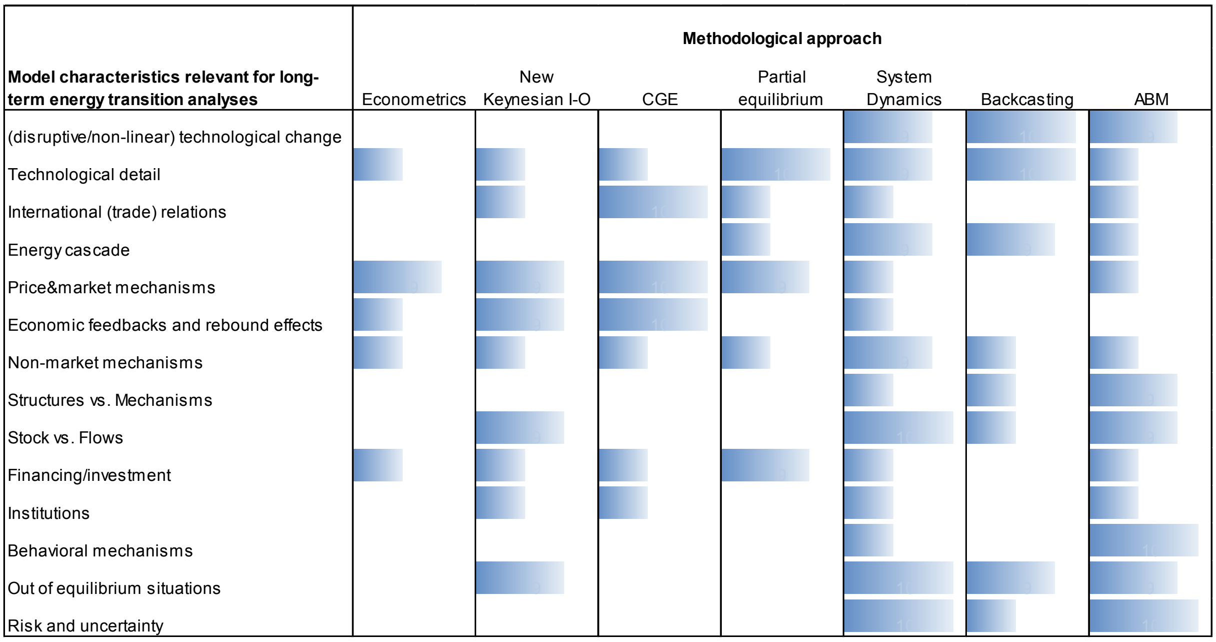
5 Conclusions

Existing energy- and climate-economic modelling approaches are increasingly seen with skepticism regarding their ability to forecast the long term evolution of economies and energy systems. The economic, climate and energy sphere are highly complex non-linear systems, so far most often only poorly dealt with when assessing the transition pathways leading to a desirable future. This Working Paper reports a structured meta-analysis of state-of-the-art national and international energy-economic modelling approaches, focusing on their ability and limitations to develop and assess pathways for a low carbon society and economy, both in total and for the main sectors contributing to greenhouse gas emissions. In particular, we set out to identify those existing models and/or model components/modules which could be of interest in developing a research plan for the creation of an open source model for analysing a national transition to a low carbon society by 2050, here more specifically applied to Austria.

We find that existing methodological approaches have some fundamental deficiencies that limit their potential to understand the subtleties of long-term energy transformation processes. Table depicts a qualitative scoreboard for different methodological approaches' capability of dealing with characteristics relevant for long-term energy transition analysis. It is important to note here that this scoreboard is only a first qualitative mapping based on the authors' expert judgement and feedback by the CLIMTRANS consortium. Most modelling approaches that were analysed (specifically econometric, computable general equilibrium, and New

Keynesian approaches) are characterised by an almost complete absence of details of the energy cascade, in particular they lack to model the central role of functionalities that are provided by the interaction of energy flows and corresponding stock variables. Further they are not well equipped for analysing radical technological changes. Model results often depend on only a single mechanism depicted by the modelling approach, e.g. for computable general equilibrium models, partial equilibrium models or New Keynesian models (relative) price changes are the key drivers. Reversely, top-down integrated assessment models aim to include as many mechanisms as possible and are hence capable of capturing feedback effects between aspects of the system under consideration (economy, climate system, society, other environment), but this comes at the cost of either (a) working on a very coarse level of detail, with e.g. only limited explicit representation of alternative technologies and using highly uncertain (e.g. damage-) functions between relating e.g. economic indices like a region's GDP and global mean temperature changes (hard-link IAMs) or (b) experiencing problems in convergence and consistency among the models used (soft-link IAMs). Bottom-up, partial equilibrium optimization models investigating energy systems are capable of depicting a rich technological detail and of identifying technologically optimal solutions (as defined by an objective function) and hence rule out inferior solutions. However, due to high computing requirements these models are limited to restricted complexity (e.g. convexity and missing macroeconomic feedbacks) and are therefore less well suited to evaluate realistic forecasts of energy system states which are far from the optimal solution as defined by the objective function, which is usually the case for real-life systems. Comparatively novel methodological approaches such as System Dynamics (SD) or Agent Based Models (ABM) do allow for representing stock-flow relationships and dynamic, disruptive transformation processes but lack the possibility to find optimal pathways (e.g. least cost, minimizing energy demand, minimizing emissions) for the transition and tend to be highly resource intensive regarding empirical data input, which is, however, critical for deriving real world relevant results. Moreover for SDs and ABMS, just as for more traditional approaches such as computable general equilibrium approaches, problems might occur regarding the separation of the structure – e.g. the elements of an energy system – from the mechanisms that are generating these structures. What is true for all modelling techniques mentioned so far is that the respective results are heavily driven by exogenous input (parameter) assumptions (e.g. price elasticities, perfect information, rational behaviour of agents, model closures) which are in turn triggering endogenous responses within the model.

Table 1 Qualitative scoreboard for different methodological approaches' capability of dealing with characteristics relevant for long-term energy transition analysis



Based on this meta-analysis we suggest that a methodological framework for analysing long-run energy and greenhouse gas emissions system transitions has to move beyond current state of the art techniques and simultaneously fulfill the following requirements: (1) inherent dynamic analysis, describing and investigating explicitly the path between different states of system variables, (2) specification of details in the energy cascade, in particular of the central role of functionalities that are provided by the interaction of energy flows and corresponding stock variables, (3) a clear distinction between structures of the energy systems and (economic) mechanisms and (4) ability to find optimal pathways (e.g. least cost, minimizing emissions, minimizing energy demand). Furthermore, a crucial task in modelling is to specify explicitly whether a model element is determined endogenously or exogenously, ideally governed by the demands of the underlying question to be answered.

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9.2 Appendix B: ClimTrans2050 Working Paper No.2: Energy modeling that matters for reality. A handbook for deepened structural modeling approaches

Energy modeling that matters for reality
A handbook for deepened structural modeling approaches

ClimTrans2050 Working Paper No. 2

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This document is intended to encourage
discovering the emerging new mindset for a better understanding of energy systems,
discarding the wrong questions concerning low-energy and low-carbon strategies,
refusing to answer these questions,
insisting that research results are not negotiable,
realizing the limits of mainstream economics for handling transformative energy system issues, and
considering that saying no is often the best answer that can be given.

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Database

All data used originate from the Austrian Energy Balance as reported in December 2015 by Statistik Austria.

If not indicated otherwise, all Figures and Tables stem from the authors based on this database.

1 Summary: Ten commandments for energy modeling that matters for reality

What went wrong with energy modeling?

Paul Krugman judged "most work in macroeconomics in the past 30 years has been useless at best and harmful at worst."(Cited in Economist June 11th 2009).

We are inclined to propose a similar, albeit more nuanced judgment for most policy analyses that are based on current energy modeling practices. The fragility of model based policy recommendations can be judged for example by the Commission's responses to discussions in the ongoing reference scenario exercises employing the PRIMES model (E3mlab, 2015; European Commission, 2016)..

We thus here follow on the work that has been enlightening, supportive in policy advice and thus extremely useful, as was the case in macroeconomics, here in the case of energy modeling.

Echoing the revealing book of Dan Rodrik (2015) about the use and misuse of economic modeling practices, we summarize our findings and recommendations for a new generation of energy modeling in ten commandments.

(1)
There is nothing like the "true" energy model

A model always is a purposeful and simplified representation of aspects of reality. The point is to figure out which model applies best in a given setting, i.e. the research question and real world constraints for modeling.

Often modelers, however, are inclined to stick to "their" model and don't admit that their available model might just not be suited for a given task. In other words: Not only the energy system is subject to the risk of being trapped in path dependencies, also energy-economic modelers are.

(2)
New challenges require a fundamentally new generation of energy models

The new challenges for energy modeling are the expansion of the time horizon way beyond the time ranges of conventional economic analyses, the assessment of disruptive transformations in highly complex non-linear socio-ecological systems, and the recognition of risks and uncertainties.

Issues like the transformation to low-energy and low-carbon structures and the upcoming disruptive technologies require a fundamentally new approach to understanding and analyzing energy systems. Most of the current generation of energy models therefore becomes obsolete if used without recognizing these new challenges.

(3)
Don't pretend that your model outcomes have a predictive quality

Model results that use statistical methods most often loose rapidly their predictive accuracy if we extrapolate beyond the sample period. The reasons for this to be the case are small sample sizes, poor data quality, structural changes and inadequate model specifications.

You therefore better critically reflect on and do not understand as prediction what the International Energy Agency is telling us about their long-term global energy forecasts in their annual World Energy Outlook or how the European Commission uses conventional modeling frameworks for justifying policy recommendation needs that go beyond a predictive

	use of data bases.
(4) **Think twice if your model is really able to answer a specific question by policy makers**	You may be inclined to make very strong, often unrealistic assumptions, e.g. when you are asked about the expected energy prices and their impacts on energy flows. You won't be able to obtain answers without referring to very strong assumptions about the behavior of households, firms and markets. If you do not communicate this modeling caveat to the actors you are advising, then this is not OK. It might also be a good decision to bring to the attention of policy makers that many of their questions about the impact of specific policy measures are rather outdated. This holds true in particular when modelers don't resist providing answers about the future of energy systems by offering model outcomes under seemingly comprehensive policy aggregation (but in fact hiding the range of crucial assumptions), as has been applied in Austria under the labeling "with existing" or "with additional" policy measures".
(5) **This is a good time for updating our understanding of energy systems**	Not only has the economic environment in general undergone a tectonic shift since 2008 when the events on the financial markets triggered the ongoing multiple-economic-crises mode. The energy sector appears to be the tip of an iceberg that signals a need to search for a better understanding of ongoing phenomena, their causes and their relevance for our well-being. Let's use this window of opportunity in a wiser way than the one that opened up after the global financial crises.
(6) **This is also a good time for extending the scope of reasoning in the context of energy issues**	In the past discussions about energy issues were dominated by speculations about the role of fossil fuels with respect to its availability and the use of market power in particular of the oil and gas producers. Related to a strongly needed reframing of the economic concept of welfare towards a more comprehensive wellbeing approach, the new understanding of energy issues also requires a different mindset with an extended vocabulary that starts with the hardly understood concept of energy related functionalities as the ultimate task to be fulfilled by our energy system.
(7) **Don't confuse agreement among modeling communities with certainty about how the energy system works**	Energy modeling exhibits a tremendous inertia because of the amount of effort needed to setup modeling frameworks and the reluctance of model builders to separate from their crafted tools. This explains why the vast majority of currently used energy models are just not adequate to deal with the new challenges that are marked by breakthrough technologies and rapid decarbonization.
(8) **A poor understanding of the energy system can't be compensated by mathematism**	Quite often model builders seem to be tempted to disguise a poor understanding of the underlying issues by sophisticated mathematics. As Nobel Laureate Paul Krugman remarked after the 2008 financial crisis took most economists by surprise: "the economics profession went astray because economists, as a group, mistook beauty, clad in impressive-looking mathematics, for truth."

You should not hesitate to reveal the related The Emperor's New Clothes effect.

(9)
It is OK to say that a specific question by a policy maker can't be answered

There are numerous examples when model builders did not resist providing answers to energy issues that just can't be reliably answered for real world circumstances.

Prominent examples are the effects of low and high oil prices or the impact of energy taxes and subsidies. Modeling results are always dependent on the respective modeling framework employed and the required assumptions and therefore only valid under this very specific abstraction from reality.

(10)
It is OK to tell policy makers that they are putting irrelevant or wrong questions, at the same time nudging them towards the questions that really matter

An honest and relevant conversation with policy makers more often should refer to the previous Command.

Strategic planning of policy conversations, potentially embedded in co-generation processes, could open policy and decision-makers eyes for the questions that really matter.

2 A primer into the new energy economics

The intention of this document is to demonstrate how our evolutionary understanding of energy systems requires an accompanying redesign and practice of energy modeling if the profession seeks to be policy relevant.

2.1 What's new in energy economics

In a nutshell basically two extensions characterize the new thinking in energy economics:

The internal structure of an energy system

The first extension discovers the internal structure of a real world energy system, which can be described by a cascade sequence:

Functionalities
as the energy services related to thermal, mechanical and specific electric tasks are the ultimate purpose of an energy system.

Technologies
as for applications in buildings, mobility, and production, and for transformations to electricity and heat determine the related energy flows.

Energy mix
as the partition of energy into fossils and renewables has impacts in particular for greenhouse gas emissions.

The external interactions of an energy system

The second extension concerns the links of the above described energy system with the broader socio-economic and institutional environment. The core of an energy system, which is characterized by its physical characteristics, communicates in an onion-like structure with the socio-economic sphere and with the institutional and behavioral sphere.

Thus we can identify three encompassing tiers for a comprehensive characterization of an energy system.

The physical tier
depicts the cascade ranging from functionalities to energy flows and their mix depending on the choice of application and transformation technologies.

The economic tier
interacts with the physical tier via consumption of energy and investments into stocks that are relevant for energy productivity and energy efficiency.

The institutional tier
provides mechanisms for coordination and incentives, as markets and regulations, and considers behavioral attitudes.

These extensions follow a reasoning that is summarized in Schleicher (2015) and roots in research projects reported in Köppl et al. (2014) and Köppl and Schleicher (2014).

2.2 What might still be going wrong

Currently the mainstream of energy economics just does not put enough attention to the internal structure of an energy system and does not disentangle the three encompassing tiers presented above. This, however, creates major problems as to the applicability of related modeling approaches for real world energy policy design.

Are selected modeling approaches fit to a particular purpose?

All currently used modeling approaches need a careful evaluation if they fit to a particular purpose. This will be demonstrated by a few examples.

Econometric methods

Statistical methods, as time series analysis or multiple relationships between energy flows, economic activity and prices, are of limited use if the time range of analysis is extended beyond the sample size. The main reasons are structural changes both within and outside the sample period.

Economic structures

The interaction of the energy sector with the other sectors of an economy is usually dealt with either on an aggregate level with GDP related components or on sectoral levels as described by input-output tables. Both approaches suffer from difficulties in dealing with structural changes and sufficient detail for identifying the relevant interactions with the energy system.

Institutional settings

Modeling approaches that deal with partial or general market equilibrium specifications intermingle the above addressed three constituting tiers and might postulate market mechanisms which either are not existent at all or not in equilibria.

2.3 What a deepened modeling approach can achieve

We demonstrate in the sequel, how an extended understanding of energy systems and the related deepened structural modeling approach can be implemented in a full-scale model of the Austrian energy system.

The focus on energy related functionalities

Starting point are databases with the following energy related functionalities:

Low temperature heat

High temperature heat

Stationary engines

Mobile engines

Lighting and electronics

This is in striking contrast to conventional approaches that focus on types of energy flows (fossil, non-fossil, heat and electricity) and economic sectors (households, transport, production).

CO_2 emissions are fully related to these

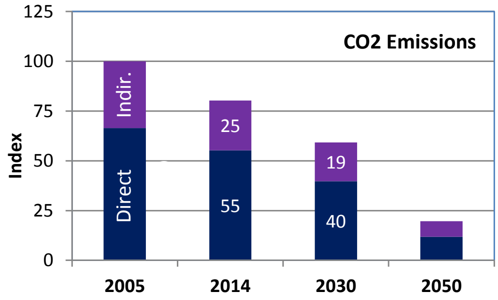
We are able to partition CO_2 emissions fully to these functionalities as demonstrated in Figure 2-1 to Figure 2-3.

functionalities

This is done by adding to the fossil energy flows needed a particular functionality also the indirect emissions via the consumption of electricity and heat and the related distribution losses.

Figure 2-1 indicates how an emissions path could look like that reduces 80% of emissions by 2050 compared to 2005.

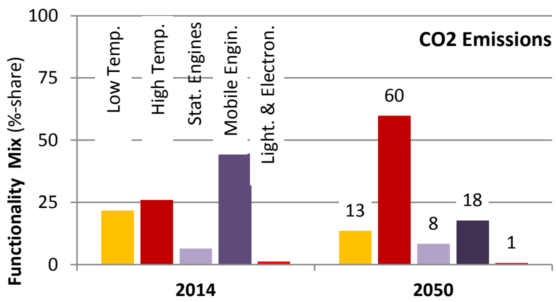
Figure 2-1 *CO_2 Emissions – direct and indirect emissions*



Emissions related to functionalities

Figure 2-3 indicates the distribution of these emissions according to the functionalities. Currently this emissions peak in mobile engines, i.e. transport activities. By 2050 the remaining emissions will be dominated by functionalities related to high temperature heat, i.e. energy intensive industrial processes.

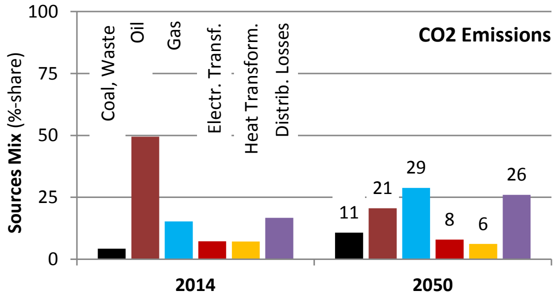
Figure 2-2 CO_2 Emissions related to functionalities



Emissions related to functionalities

Figure 2-3 depicts the distribution of these emissions according to the types of energy used for providing the functionalities. Currently these emissions mainly originate from oil products. By 2050 the remaining emissions show peaks in gas and distribution losses.

Figure 2-3 CO_2 Emissions related to energy types



3 In a nutshell: The building blocks for a deepened structural energy modeling approach

Essential for a deepened structural approach to modeling energy systems is the distinction between the physical structure, its interaction with the socio-economic system and the institutional embedding with its mechanisms for coordination and incentives.

3.1 Tier one: The physical structure of the energy system

The physical structure of the energy system exhibits a cascade structure which spans from functionalities (thermal, mechanical, specific electric) via final energy flows (fossils, renewables, heat and electricity) to primary energy flows (fossils, renewables, nuclear). Each stage of this cascade is related to specific capital stocks.

3.1.1 The energy cascade for providing functionalities

Observing application and transformation technologies

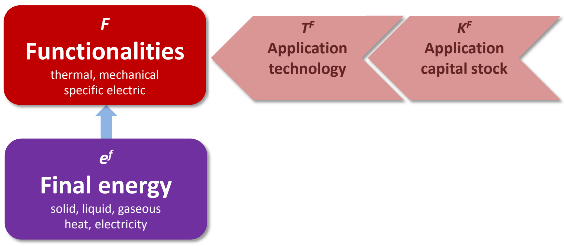
Functionalities and application technologies

Starting point is the provision of the functionalities F which result from final energy flows e^f and from the capital stock K^F that comprises the application technologies $T^F(.)$:

(1.1a) $F = T^F(e^f, K^F)$

This key relationship of any energy system is depicted in Figure 3-4.

Figure 3-4 Provision of functionalities



Final energy via transformation technologies

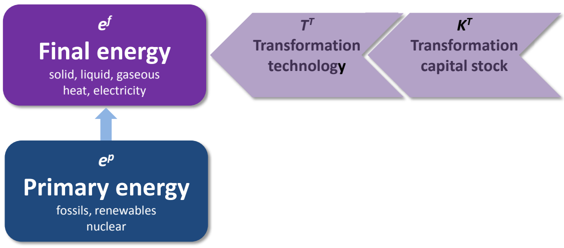
Final energy flows e^f result from primary energy flows e^p by using transformation technologies $T^T(.)$ with the related capital stock K^T:

(1.1b) $e^f = T^T(e^p, K^T)$

We include in our definition of transformation technologies also any distribution activities via networks.

Figure 3-5 indicates these transformation activities of an energy system.

Figure 3-5 Transformation and distribution of energy



Switching to application and transformation productivities

Parametrization with productivities

We parameterize the relationships (1.1) by describing the application and transformation technologies by their productivities $t^F(K^F)$ and $t^T(K^T)$ which in turn reflect the related capital stocks:

(1.2a) $F = t^F(K^F)\cdot e^f$

(1.2b) $e^f = t^T(K^T)\cdot e^p$

Advantages of this implementation

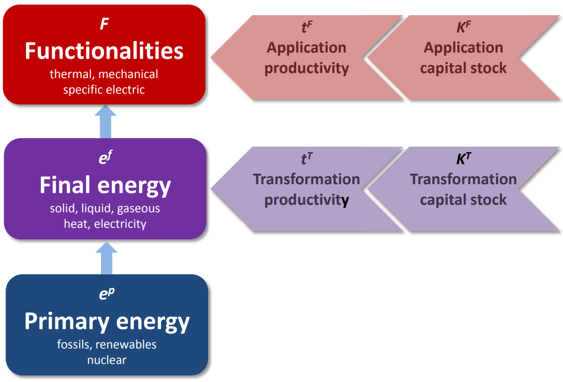
This parametrization is highly supportive for a databased implementation.

The application productivity $t^F(K^F)$ depicts the amount of functionalities, e.g. the volume of heated space, obtained from one unit of final energy. The productivity itself is dependent on the quality and quantity of the related capital stock of the application technology.

Similarly the transformation productivity $t^T(K^T)$ indicates the mass efficiency of a transformation process, namely the amount of final energy obtained from one unit of primary energy.

Figure 3-6 illustrates this parameterization and reveals also the characteristic cascade structure of the energy system.

Figure 3-6 The cascade structure of the energy system



Choosing application and transformation technologies

The basic relationships (1.2), which describe the application and transformation activities of an energy system, can be condensed to

(1.3a) $F = t^F(K^F)\cdot t^T(K^T)\cdot e^p$ *or*

(1.3b) $e^p = t^F(K^F)^{-1}\cdot t^T(K^T)^{-1}\cdot F$

Representation (1.3b) of the physical structure of an energy system reveals how for a given amount of functionalities the demand for primary energy can be reduced by improving the application and transformation efficiency of the system, which in turn requires improvements in the related capital stocks.

Inversion of the reasoning

Relationship (1.3b) also serves what is coined the inversion of the reasoning, i.e. a reversal of the usual flow of argumentation when dealing with energy systems. Instead of starting with primary energy and following its way through the energy system, deliberately the analysis begins with a focus on functionalities, then elaborates options for choosing application and transformation technologies and finally ends up with primary energy requirements.

3.1.2 Adding greenhouse gas emissions

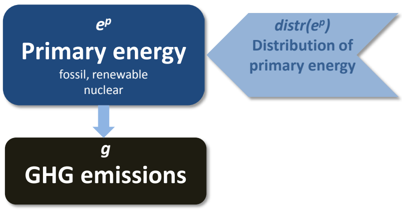
Choosing the energy mix

We now consider in our physical model of an energy system the role of the energy mix, i.e. the distribution of primary energy, which we partition into fossil, renewable and nuclear.

Determining greenhouse gas emissions

This distribution of primary energy is closely tied to all kinds of emissions from energy use, in particular greenhouse gas emissions resulting from fossils, as indicated in Figure 3-7.

Figure 3-7 Greenhouse gas emissions from energy use



Emissions intensity of fossil primary energy

We parameterize greenhouse gas emissions by tying their volume g is tied to the flow of fossil primary energy $e^{p,fos}$ via the emissions intensity g^{fos} of this flow:

(1.4) $g = g^{fos} \cdot e^{p,fos}$

This emissions intensity in turn is dependent on the distribution, namely energy mix, of the fossil primary energy $distr(e^{p,fos})$:

(1.5) $g^{fos} = g^{fos}(distr(e^{p,fos}))$

Shares of renewable and nuclear primary energy

By partitioning total primary energy into its fossil, renewable and nuclear component

(1.6) $e^{p} = e^{p,fos} + e^{p,res} + e^{p,nuc}$

and defining their shares in total primary energy by $s^{p,\ fos}$, $s^{p,res}$ and $s^{p,nuc}$ *respectively, we obtain*

(1.7) $1 = s^{p,fos} + s^{p,res} + s^{p,nuc}$

We can link now the volume of greenhouse gas emissions to the emissions intensity of fossil primary energy and the shares of renewables and nuclear in total primary energy:

(1.8) $g = g^{fos}(distr(e^{p,fos}))\cdot(1 - s^{p,fos} - s^{p,res} - s^{p,nuc})\cdot e^{p}$

3.1.3 Summarizing the physical structure of the energy system

The constituting features

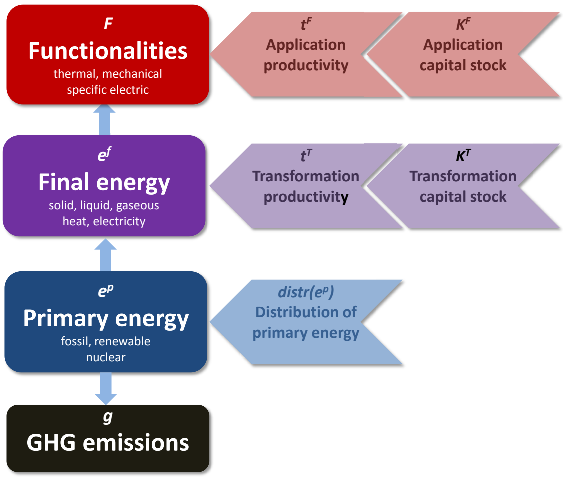
Collecting the elements that describe the physical structure of the energy system, we arrive at Figure 3-8 with the following constituting features:

A cascade structure with the focus on functionalities and the supporting energy flows via final and primary energy.

The accompanying technologies for application and transformation purposes which in turn determine the productivity of the energy flows.

The distribution of the energy mix with respect to fossil and non-fossil components which determines the carbon and other greenhouse gas emissions.

Figure 3-8 The physical structure of the energy system



The analytical model

Basic model of the physical tier

Corresponding to the cascade structure we obtain the following recursive set of equations for the basic model that describes the physical structure of the energy system and the related greenhouse gas emissions.

Final energy flows

(1.9a) $e^{f} = t^{F}(K^{F})^{-1}\cdot F$

Primary energy flows

(1.9b) $e^{p} = t^{T}(K^{T})^{-1}\cdot e^{f}$

Greenhouse gas emissions

(1.9c) $g = g^{fos}(distr(e^{p,fos}))\cdot(1 - s^{p,fos} - s^{p,res} - s^{p,nuc})\cdot e^{p}$

Variables and parameters

This is a list of variables and parameters that are used in the basic physical model.

Functionalities

F functionalities

Energy flows

e^{f} final energy flows

e^{p} primary energy flows

$e^{p,fos}$ primary energy flows, fossil

$e^{p,res}$ primary energy flows, renewable

$e^{p,nuc}$ primary energy flows, nuclear

Technologies

T^{F} application technologies for providing functionalities

T^{T} transformation technologies for converting primary into final energy

Productivity

t^{F} application productivity for providing functionalities

t^{T} transformation technologies for converting primary into final energy

Capital stocks

K^{F} capital stock for application technologies

K^{T} capital stock for transformation technologies

Greenhous gas emissions

g greenhouse gas emissions volume

Parameters

$s^{p,fos}$ primary energy share, fossil

$s^{p,res}$ primary energy share, renewable

$s^{p,nuc}$ primary energy share, nuclear

g^{fos} greenhouse gas emissions intensity of fossil fuels

$distr(e^{p,fos})$ distribution of energy mix of fossil fuels

3.2 Tier two: Embedding energy into the economic system

The energy system and the economic system interact mainly via two channels: energy flows and investments for the infrastructure which determine the productivity of energy for providing energy services.

3.2.1 Links between the energy system and the economic system

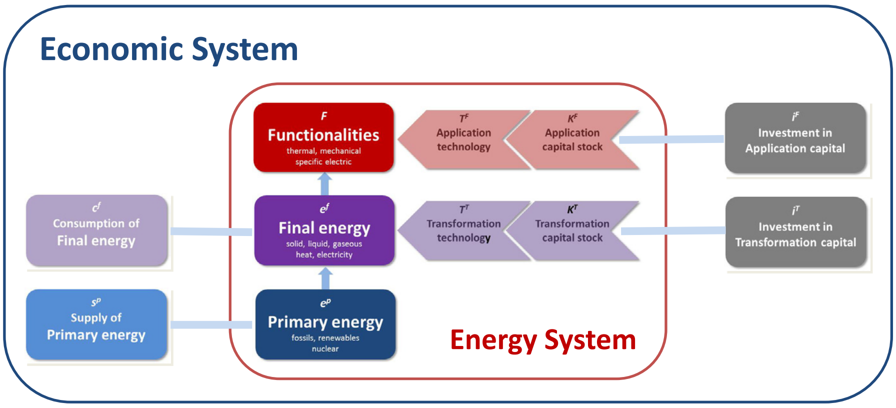
As can be visualized in Figure 3-9, the energy system as described in tier one is embedded with following linkages into the economic system, which we identity as tier two in our modeling framework:

Energy flows, as final and primary energy, e^f and e^p, respectively.

Investments into the capital stocks for application and transformation technologies.

Both types of physical energy flows of the energy system are in the economic system converted via appropriate prices into monetary units.

Figure 3-9 Embedding the energy system into the economic system



Links via energy flows and investments

Links via energy flows

Both types of physical energy flows of the energy system are in the economic system converted into monetary units via appropriate prices.

Assuming a representative energy price p^e, then final energy e^f shows up in the economic system as consumption of energy c^e

(2.1a) $c^e = p^e \cdot e^f$

and primary energy e^p corresponds in the economic system as energy supply s^e

(2.1b) $s^e = p^e \cdot e^p$

Links via investments

Two investment activities in the economic system are relevant for the technologies of the energy system and its related productivities, namely investments into the application and the transformation capital stock.

Investments i^F in the capital stock for application technologies are determined by changes of this capital stock ΔK^F and replacement investments r^F:

(2.2a) $i^F = \Delta K^F + r^F$

Similarly investments i^T in the capital stock for transformation technologies result as:

(2.2a) $i^T = \Delta K^T + r^T$

3.2.2 Basic relationships of the economic system

We proceed by partitioning the economic system into two sectors:

The energy sector
: covers all activities that relate from the supply of primary energy to the provision of functionalities.

The non-energy sector
: deals with the remaining activities of the economy and may be further disaggregated into subsectors.

Energy sector of the economic system

The supply of the energy sector s^e is provided by domestic production q^e and imports m^e:

(2.3a) $$s^e = q^e + m^e$$

The demand of the energy sector d^e comprises consumption of energy c^e for households, companies and the public sector as well as exports of energy x^e:

(2.3b) $$d^e = c^e + x^e$$

Non-energy sector of the economic system

Similarly the supply of the non-energy sector s^n results from domestic production q^n and imports m^n:

(2.4a) $$s^n = q^n + m^n$$

The demand of the non-energy sector d^n deals with consumption of non-energy c^n (for households, companies and the public sector) but also adds investments i^n for this sector and for the energy sector i^F and i^T for the application and transformation capital stock as well as exports of non-energy products:

(2.4b) $$d^n = c^n + i^n + i^F + i^T + x^n$$

Both in the energy and non-energy sector an additional demand component for inventory changes could be added.

The essence of a structural specification

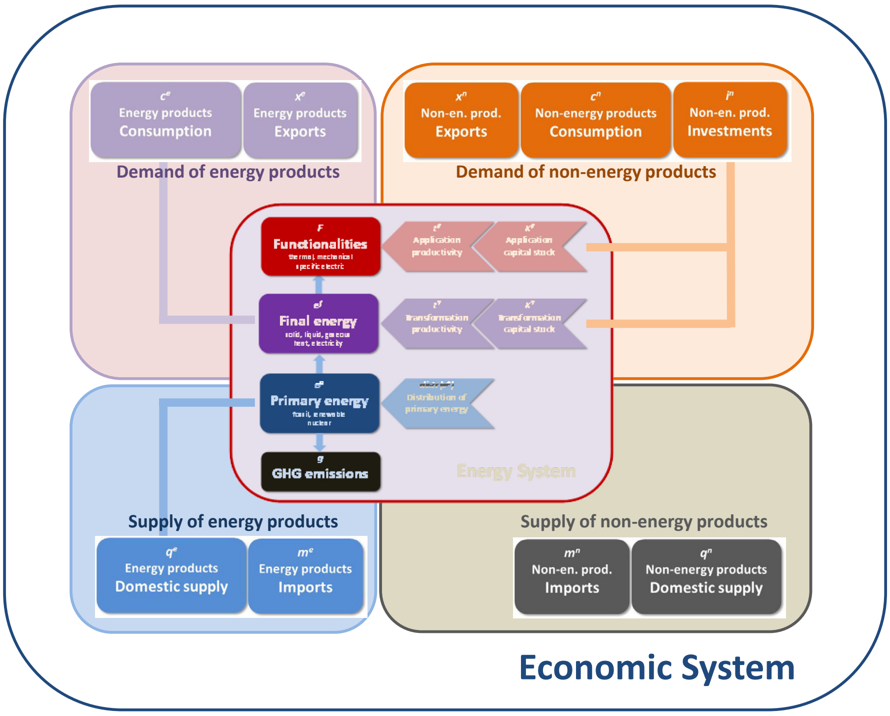
At this point of the exposition of the deepened modeling framework it seems worth reminding that so far we have only proposed relationships that describe either physical identities, as in the energy system of tier one, or monetary identities without claiming any causalities or behavioral assumptions. This will explicitly be dealt with in tier three.

We therefore do not postulate, e.g., in tier two of our modeling framework that demand will equal supply either in the energy or in the non-energy sector.

3.2.3 Summarizing the basic structure of the economic system

Figure 3-10 visualizes how the energy system interacts with the economic system. The main linkages are the flows of final and primary energy and the investments that determine the productivity of the application and transformation technologies.

Figure 3-10 Interactions between the energy system and the economic system



The analytical model

Links between the energy and the economic tier

The links via energy flows:

Consumption of final energy

(2.5a) $c^e = p^e \cdot e^f$

Supply of primary energy

(2.5b) $s^e = p^e \cdot e^p$

The links via investments:

Investments in the capital stock for application technologies

(2.5a) $i^F = \Delta K^F + r^F$

Investments in the capital stock for transformation technologies

(2.5b) $i^T = \Delta K^T + r^T$

Basic model of the economic Tier

The basic supply and demand relationships for the economic model:

Supply of the energy sector

(2.6a) $s^e = q^e + m^e$

Demand of the energy sector

(2.6b) $d^e = c^e + x^e$

Supply of the non-energy sector

(2.7a) $s^n = q^n + m^n$

Demand of the non-energy sector

(2.7b) $d^n = c^n + i^n + i^F + i^T + x^n$

Variables and parameters

This is a list of variables and parameters that are used in the basic economic model.

Energy flows in physical units

e^f	final energy flows
e^p	primary energy flows

Energy products in monetary units

d^e	demand of final energy products
c^e	consumption of final energy products
x^e	exports of final energy products
s^e	supply of primary energy products
q^e	domestic supply of primary products flows
m^e	imports of final energy products

Non-energy products in monetary units

d^n	demand of non-energy products
c^n	consumption of non-energy products
i^n	investments in non-energy capital stock
i^F	investments in application technologies capital stock
i^T	investments in transformation technologies capital stock
x^n	exports of non-energy products
s^n	supply of non-energy products
q^n	domestic supply of non-energy products
x^e	exports of non-energy products

Capital stocks in monetary units

K^F	capital stock for application technologies
K^T	capital stock for transformation technologies

Prices

p^e	energy price

3.3 Tier three: Considering coordinating institutions, attitudes and incentives

We have discovered so far how the energy system is embedded in the economic system. We continue by asking how in this onion-like structure in an additional tier the economic system is driven by institutions and mechanisms for coordination and shaped by attitudes and incentives.

3.3.1 Causality driven interactions

In the two tiers considered so far no interactions based on postulated causalities were specified. We proceed now by taking into account the possibility of causalities based on economic activities and prices.

Activity based interactions

Non-energy sector

There is strong empirical evidence that in the non-energy sector the main components of demand, as consumption c^n and investment i^n, and the supply from imports m^n respond to indicators of economic activity as the volume of production in the non-energy sector q^n:

(3.1a) $c^n = c^n(q^n)$

(3.1b) $i^n = i^n(q^n)$

(3.1c) $m^n = m^n(q^n)$

In an econometric specification these relationships are parameterized by income elasticities. The related issue is the stability and validity of these parameters beyond a sample period.

Energy sector

Similar causal relationships may be postulated for the energy sector by postulating that consumption of energy c^e is caused by final energy flows e^f and domestic supply q^e and foreign supply m^e are driven by primary energy flows e^p:

(3.2a) $c^e = c^e(e^f)$

(3.2b) $q^e = q^e(e^p)$

(3.2c) $m^e = m^e(e^p)$

The related econometric specifications by energy elasticities need also to be checked with respect to stability and validity.

Physical energy system

Causal feedbacks may be proposed from the economic tier also to the physical energy system.

The amount of functionalities could be influenced by economic activity in the non-energy sector q^n and the related incomes:

(3.3) $F = F(q^n)$

Although this seems to be a plausible assumption, an econometric specification meets limits with respect to the availability of time series for functionalities.

Price based interactions

Non-energy sector

Hypothesis about price driven interactions for the non-energy sector would involve the following specifications for consumption c^n and investment i^n as well as domestic q^n and foreign supply m^n, depending on domestic and foreign prices p^q and p^m, respectively:

(3.4a) $c^n = c^n(p^q)$

(3.4b) $i^n = i^n(p^q)$

(3.4c) $q^n = q^n(p^q)$

(3.4d) $m^n = m^e(p^m)$

These relationships are typically parameterized by price elasticities. Data analysis based on econometric methods reveals that the significance of these relationships is rather fragile.

Energy flows

Price driven hypotheses for the supply and demand of energy flows, either in physical or in monetary units, typically postulate relative prices between various energy types p^e and not-energy prices p^q being relevant:

(3.5a) $e^{supply} = e^{supply}(p^e/p^q)$

(3.5b) $e^{demand} = e^{demand}(p^e/p^q, q^n)$

The specified direct and cross-price reactions, mostly parameterized as elasticities, need strong additional assumptions from neoclassical demand theory in order to obtain estimates based on time series samples.

Energy mix

For the distribution of the primary energy mix $distr(e^p)$ energy prices p^e could be considered:

(3.6) $distr(e^p) = d(p^e)$

A verification of such a hypothesis by data analysis is even more difficult because of the underlying investment activities, which in turn may be driven by non-price decisions.

3.3.2 Market-based coordination

As a next step in our exposition of modeling designs we introduce hypotheses about the overall coordination mechanism.

Although markets seem to be the preferred coordination mechanism for economic activities this is not necessarily based by evidence if we are dealing with the energy sector. Even if we stick to market mechanism, it is useful to distinguish between a Keynesian type and a neoclassical type of market coordination.

Keynesian type coordination

A Keynesian type market coordination would assume that supply basically adjusts to demand, thus giving less attention to potential supply restrictions.

In the sequel we partition the economy into a non-energy and energy sector and denote the relevant economic variables by superscripts *n* and *e*, respectively.

Quantity equilibrium of the non-energy sector

Stating total supply of the non-energy sector by domestic production q^n and imports m^n and total demand by consumption c^n, investments i^n and exports x^n, the quantity equilibrium for the non-energy sector would require:

(3.7a) $q^n + m^n(q^n) = c^n(q^n) + i^n(q^n) + x^n$

Since this specification also allows some components to react with respect to domestic economic activity q^n, any additional demand will generate multiplier impacts.

Quantity equilibrium of the energy sector

Similarly we obtain a quantity equilibrium for the energy sector. We postulating that demand components comprise energy consumption c^e, which is driven by the volume of final energy consumption e^f, and energy exports x^e. We further assume that this energy demand is fully met by domestic supply q^e and imports m^e, both driven by the volume of primary energy e^p:

$$(3.7b) \quad q^e(e^p) + m^e(e^p) = c^e(e^f) + x^e$$

Neoclassical type coordination

A neoclassical type market coordination emphasizes the role of prices for equilibrating demand and supply, thus considering at least some supply restrictions.

Price equilibrium of the non-energy sector

A neoclassical flavored specification for the non-energy sector postulates the dependency of demand and supply components from the domestic price p^q and the import price p^m:

$$(3.8a) \quad q^n(p^q) + m^n(p^m) = c^n(p^q) + i^n(p^q) + x^n$$

Under the assumption that there is a price adjustment for products of the non-energy sector towards an equilibrium between supply and demand, this equilibrium price $p^{q,equ}$ will determine the quantities of the supply and demand components.

Price equilibrium of the energy sector

For the energy sector a neoclassical setting would postulate demand and supply relations for final and primary energy and again a price adjustment towards a market equilibrium:

$$(3.8b) \quad e^{supply}(p^e/p^q) = e^{demand}(p^e/p^q, q^n)$$

In our basic model such a price equilibrium could be postulated for the energy sector:

$$(3.8c) \quad q^e(p^e/p^q) + m^e(p^e/p^q) = c^e(p^e/p^q) + x^e$$

Thus the interacting equilibria of the non-energy sector (3.8a) and the energy sector (3.8c) would determine equilibrium prices $p^{q,equ}$ and $p^{e,equ}$, respectively, which in turn would determine the corresponding non-energy and energy quantities.

It is obvious that all actors in the energy and non-energy sector would need a substantial amount of information in order to end up in these interacting equilibria.

3.3.3 Non-market based coordination and incentives

The energy sector typically reflects many economic decisions that are not based on markets but incentives from the non-market agenda, in which also vested interests may be of stronger relevance.

Path dependency

Most decisions in the energy sector are determined by the relevant infrastructure or the capital stocks that determine the available application and transformation technologies. This is the existing stock of buildings and machinery, the network of roads and railways, and past investments for generating and providing energy.

Many policy decisions, as the building of hydro generation units on the Danube and hydro storage in the Alps or the nuclear power plants in France are by-products of military strategies. Other energy infrastructure, as the railway system of Switzerland or the public transportation system in Vienna has been deliberately motivated by offering these services to the society.

Over the past years investments into roads have in Europe in almost all states obviously by far exceeded those into railways. These facts create path dependencies and just can't be easily reversed, e.g. by energy prices.

Deepened structural models should be able to handle these path dependencies and to assist in identifying windows of opportunity for transformative changes in the energy system.

What motivates energy related decisions by consumers?

Consumers seem to be in their energy related choices in particular dependent on infrastructure that was decided upon by other entities, either private or public. It is this dependency that motivates regulations, which enhance decisions that serve both the interest of investors of infrastructure and their users.

What motivates energy related decisions by companies?

With respect to energy related decisions in companies, at least between those in the energy sector and the non-energy sector needs to be distinguished.

In the non-energy sector, in particular in energy intensive industries, there is an inherent interest for cutting energy costs by improving energy efficiency. This motivation holds also for all other resources.

The energy sector is facing increasing decision problems, which are rooted in the emerging transition of the structures of this sector. There are obvious vested interests, e.g. in the fossil industry and the closely linked automobile industry, at least to slow down this transition.

Ultimately the current energy sector will need to be completely redefined by switching from a business model based on selling energy flows to a business model that offers the provision of energy related functionalities.

What regulation drives transitions?

There are no easy answers about a recommended regulatory setup that would enhance innovation towards desired structural changes, in particular to low-energy and low-carbon structure in the energy system.

We definitely can't rely only on charismatic persons like Elon Musk whose electric storage technology and electric cars may become a game changer for the electricity grid and private transport.

We are currently experiencing a penetration of technologies for renewables which was unexpected just a few years ago.

We are able to discover, however, many superficial barriers for innovation, as open or hidden subsidies for fossils or the prohibition to build private electricity grids.

What is more, we have to move beyond a purely technology-centered approach to foster transitions in the energy system. Social innovations, such as changes in lifestyles, are currently prohibited by implicit social norms and basic capitalistic incentive structures but would have to be brought in line with the planetary boundaries we are facing.

The relevance to model designs

All these aspects considered so far with respect to non-market based coordination and incentives have implications for the design of models. Again it is the recommendation to deepen the structural specifications in order to improve the handling of these issues.

3.4 More tiers: International and global interactions

The modeling framework that has been developed so far within a three tiers structure can be further embedded into international and global interactions. Two of them deserve particular attention, namely the impact of global emissions constraints and the carbon content of international trade flows.

3.4.1 Implications of global emissions constraints

Global emissions constraints

National energy policies are subject to global emissions constraints. Jonas and Zebrowski (2016) present national reduction targets under the following assumptions:

Global per capita GHG emissions equity is achieved by 2050 (meaning that in 2050 the limit of emissions required to support living and wellbeing of any individual will be equal for anyone, regardless of his/her nationality, age, etc.)

Net emissions from land-use change (LUC) are reduced linearly to zero until 2050

The remainder of the unmanaged biosphere returns also to an emissions balance (zero net emissions) until 2050.

Implications for Austria

The first part of *Table 3-1* summarizes the implications of global GHG emissions budgets for the period 2000 – 2050 corresponding to warming targets of 2 °C, 3 °C, 3 to 4 °C and above 4 °C for the cumulative emission constraints relevant to Austria.

The second part of this table presents levels of Austria's per capita emissions as of 2010 and required 2050 levels of these emissions (together with percentage reductions) corresponding to the considered warming targets.

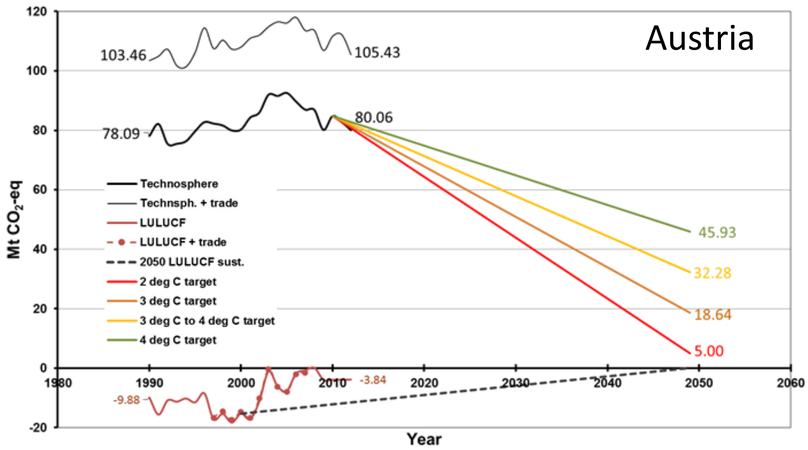
Table 3-1: Implications of global emissions constraints for Austria

			Warming target			
			2 °C	3 °C	3 °C - 4 °C	≥4 °C
Sector	2000 - 2010 cumulative emissions w/o trade	2000 - 2010 cumulative emissions with trade	2010–2050 cumulative emission w/o trade			
	Mt CO_2-eq	Mt CO_2-eq	Mt CO_2-eq	Mt CO_2-eq	Mt CO_2-eq	Mt CO_2-eq
Techno-sphere	1037.72	1351.79	1796.10	2068.96	2341.83	2614.69
LUC	-61.03	unknown	-242.45 (Imperative: Net emissions from LUC reduce linearly to zero until 2050!)			
Sector	2010 Per-capita emissions w/o trade	2010 Per-capita emissions with trade	2050 Global emissions equity target [in t CO_2-eq/cap]			
			0.6	2.1	3.6	5.2
			2010–2050 emission reduction w/o trade			
	t CO_2-eq/cap	t CO_2-eq/cap	% / cap	% / cap	% / cap	% / cap
Techno-sphere	10.11	13.31	94	79	64	49
LUC	-0.46	unknown	100% (Imperative: Net emissions from LUC reduce linearly to zero until 2050!)			

Source: Jonas and Zebrowski (2016, Table 13)

Figure 3-11 presents Austria's historical GHG emissions and linear GHG emission reduction (target) paths as of 2010 enabling Austria to meet agreed warming levels of 2 °C to 4 °C in 2050 and beyond.

Figure 3-11 Austria in an emissions constrained world



Source: Jonas and Zebrowski (2016, Figures 10b – 13b compiled)

3.4.2 Carbon content of international trade flows

Production-Based Accounting (PBA) versus Consumption-Based

Conventional greenhouse gas (GHG) emission inventories record emissions released by the agents (e.g. industries or residents) within the

Accounting (CBA)

geographical borders of a nation. This territorial emission accounting framework, also known as Production-Based Accounting (PBA), is the approach used by the United Nations Framework Convention on Climate Change (UNFCCC).

Studying emissions from a Consumption-Based Accounting (CBA) perspective, commonly referred to also as Carbon Footprints (CF), provides a complementary perspective to PBA (Peters and Hertwich, 2008; Davis and Caldeira, 2010). Emission inventories using CBA record emissions induced by residents' consumption irrespective of where in the world those induced emissions take place.

Accounting emissions along the supply chain of a product

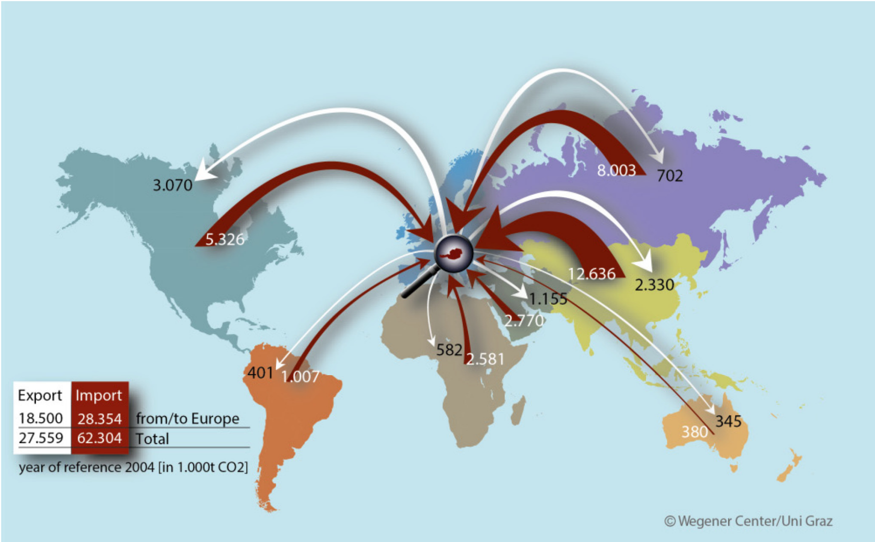
Since production and consumption occur very often in different geographical locations, these two distinct emission accounting frameworks tend to show different pictures on the amount of emission allocated to a nation which could potentially serve as a policy base (for an evaluation of the relative advantages and shortcomings of the latter see Steininger et al., 2015).

Regarding CBA emissions, one could for example think of the emissions generated in the production of a car imported from China. However, emissions might not only occur in China but throughout the supply chain, such as in countries exporting inputs to China. In the case of CBA, all the emissions occurring along the production chain are attributed to the final consumer of the car.

CBA evidence for Austria

Alternative emission inventories propose attributing emissions to the consumers inducing emissions irrespective of where in the world those induced emissions take place. To enable effective consumption-based policy design we first need to understand which products are the most intensive ones in embodied emissions in trade, and where in the world and in which activities their implicit emissions are triggered. For Austria findings include that: i) the emissions needed to sustain Austria’s consumption are 50% larger than those reported by the conventional production-based accounting system (for their regional structure see Figure 3-12); ii) more than a third of national consumption-induced emissions occur outside the EU-28 where none of the EU-caps applies; and iii) the single most important sector abroad where these emissions occur is electricity generation.

Figure 3-12 Carbon content of Austrian foreign trade



Source of data: Munoz and Steininger (2010)

3.5 Dealing with uncertainty

Uncertainties within model based energy policy analyses have to be adequately dealt with in order to enable modeling outputs to be used as a sound basis for policy recommendations and eventually the design of real world energy policy.

3.5.1 Classifying uncertainty

Classification of uncertainty according to nature and source

Uncertainties can be classified along different lines, depending on the context and scope. It is largely agreed that uncertainty is comprised of (at least) two different dimensions: the inherent nature of the uncertainty (epistemic or aleatory) and the location or source of uncertainty, which describes where, in applied situations such as energy modeling, the uncertainty manifests.

Epistemic and aleatory uncertainty

While *aleatory uncertainty* (or *statistical uncertainty*) describes the inherent randomness and natural variability of complex socio-ecological systems and their components, epistemic uncertainty (or systematic uncertainty) results from imperfect knowledge about the system under consideration. Though quantifiable with probabilistic modeling techniques, aleatory uncertainty is typically seen as irreducible (Skinner et al., 2014; Uusitalo et al., 2015). Epistemic uncertainty on the other hand can be quantified and reduced by increasing relevant knowledge. Translated to energy modeling, this requires improving modeling techniques and there underlying assumptions regarding structures (cause-effect processes) and functional forms, as well as quality of input data.

Sources of uncertainty

Focusing on environmental risk assessment, Skinner et al. (2014)

identified seven main *sources* (or *location-types*) of uncertainty that are also relevant for energy-economic modeling:

Table 3-2: Sources of uncertainty relevant for modeling

Nature of uncertainty	Source of uncertainty	Definition
Epistemic	**Data uncertainty**	The *availability*, *precision*, and *reliability* of input data is a crucial driver of modeling results. Identifying potential sources of uncertainty within input data, whether experimental or empirical, can help to distinguish between reliable and unreliable sources.
	Language uncertainty	Linguistic uncertainties stem primarily from a lack of clarity in e.g. expressing ideas or communicating results. They comprise three types: ambiguity, underspecificity and vagueness.
	System uncertainty	Can be defined according to the source pathway–receptor relationship, which constitutes the three main phases of system understanding: *cause*, which concerns a lack of clarity regarding the source(s) of an outcome; effect, relating to the influence a particular source has upon the *receptor(s)*; *process*, which concerns either not understanding the risks or not identifying something vital to a successful assessment.
	Model uncertainty	Any model is a simplified and purposeful abstraction from reality – simplifications and assumptions are necessary features of the modeling process. Nevertheless, a (conceptual) model always has to be fit for purpose and capture the essential features – no more, no less – of the real-world system. Next to parameter and output uncertainty, the most important form of model uncertainty is related to structure, i.e. the representation of real-world cause-and-effect processes.
Aleatory	**Variability or natural uncertainty**	Is the inherent unpredictability of any human or natural system and thus cannot be reduced or eliminated.
	Extrapolation uncertainty	Is based on unavailability of adequate information and data, which may require extrapolation of existing data. When extrapolation becomes necessary, the related uncertainty is aleatory in nature due to the natural variability involved. An increase in epistemic knowledge may prevent the need for extrapolation.
Combination	**Decision uncertainty**	Exists when multiple options, often accompanied by differing objectives (by different actors), are

		available to satisfy (part of) the criteria leading to a decision.

3.5.2 Reducing uncertainty by deepened structural modeling

We suggest that our extended understanding of energy systems and the related deepened structural modeling approach can be a powerful framework to tackle and reduce epistemic uncertainties in energy-economic modeling.

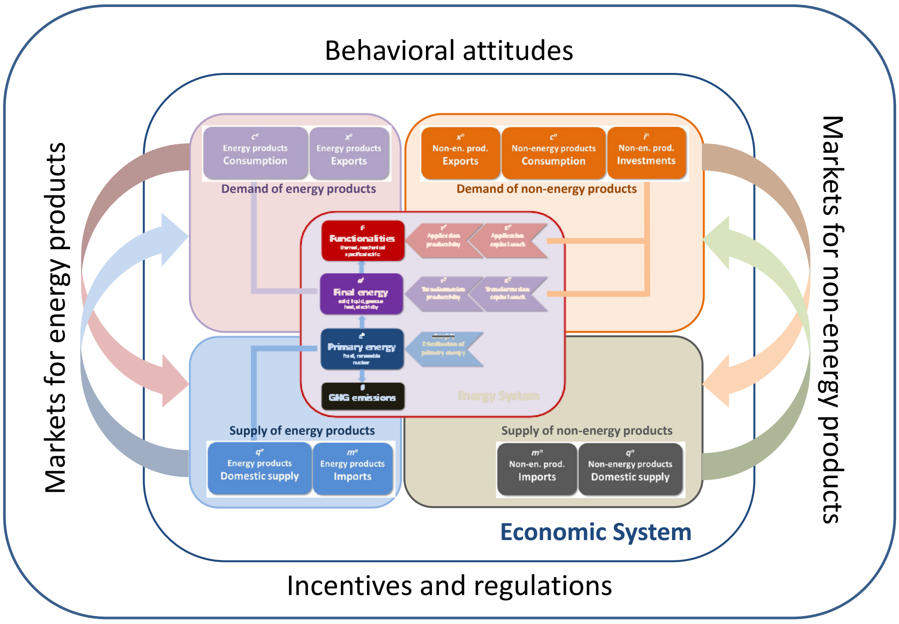
Reducing epistemic uncertainty with deepened structural modeling

The deepened structural modeling approach increases the knowledge on and strengthens the representation of (1) the external interactions of an energy system with the socio-economic and institutional systems as well as (2) the internal structure of an energy system by emphasizing the role of functionalities as the ultimate purpose of an energy system. In doing so it significantly reduces to sources of epistemic uncertainty, *system uncertainty* and *model uncertainty*, and may also contribute to the reduction of a third source, namely *language uncertainty*, by clearly expressing the eventual purpose of an energy system and posing the relevant questions that matter in reality.

3.6 Caring for caveats: The essentials of deepened structural modeling

Based on this exposition of the essential components and design aspects that constitute a deepened structural modeling framework, we are able to draw some conclusions. With them we want to encourage caring for the caveats that have been discovered.

Figure 3-13 Embedding the energy and the economic system into the institutional framework



Discovering the onion-like structure of the overall system

An overall perspective of this modeling framework is summarized in Figure 3-13 which exhibits the embedding of the energy and the economic system into the institutional framework in an onion-like structure.

Extending the exposition of the physical energy system

At the core we identify the energy system, which is represented by the interaction of physical energy flows together with application and transformation technologies for providing the welfare-relevant energy related functionalities.

This tier, however, is almost completely missing in conventional energy models and needs to be developed in much more detail. With reasonable effort this is possible since we are dealing mainly with physical phenomena.

Improving the links from the energy system to the economic system

The tier representing the economic system is measured by monetary units and is mainly linked via energy flows and investment activities with the energy system. Remarkably, conventional models do not adequately distinguish this differentiation between interactions in the operating mode from the investment mode. This differentiation, however, is essential for evaluating the impact of investments in the energy sector on its productivities and on its impacts on the non-energy sector.

Considering the institutional setting

Finally, we realize that the economic system is exposed to a multi-facet institutional setup which ranges from various types of market designs to a portfolio of incentives and a seemingly incomprehensible role of personal attitudes.

Paradoxically it is this tier which is given most implicit weight in conventional modeling, mainly by specifying behavioral assumptions rooted in the neoclassical economic paradigm. Yet, such modeling seems to be of too little differentiation.

It is probably this feature of conventional modeling that deserves to undergo a creative destruction by being replaced with much more sophisticated approaches. This requires, however, major research efforts.

4 Implementation of the modeling tool on different platforms

4.1 Implementation in Excel

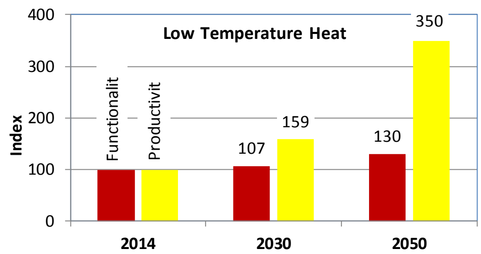
Figure 4-14 Visualization of Low Temperature Heat

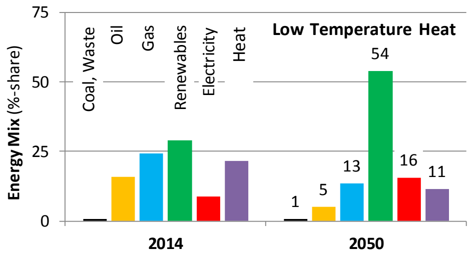
Step 1 **LOW TEMPERATURE HEAT** Start Back Next sGAIN Energy Austria

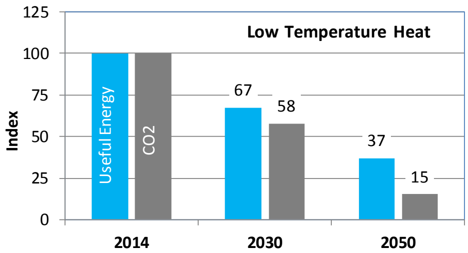
Functionalities and Useful Energy			Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Low Temperature Heat	2014	TJ	**288,241**	2,031	46,037	70,410	83,032	24,960	61,770

	Functionality	Productivity					Start Period Energy Mix			
2014	*100*	*100*	*Index*	*100*	*1%*	*16%*	*24%*	*29%*	*9%*	*21%*
							Change of Energy Mix			
Change	*30*	*250*	*Index*	*-63*	*0%*	*-11%*	*-11%*	*25%*	*7%*	*-10%*
							End Period Energy Mix			
2050	*130*	*350*	*Index*	*37*	*1%*	*5%*	*13%*	*54%*	*16%*	*11%*

2050	TJ	**107,061**	754	5,323	14,376	57,606	16,765	12,237







Proceed to the Model Modules

- Step 1: Low Temperature Heat
- Step 2: High Temperature Heat
- Step 3: Stationary Engines
- Step 4: Mobile Engines
- Step 5: Lightening and Electronics
- Step 6: Non-energetic Use
- Step 7: Energy Distribution
- Step 8: Energy Transformation

Look up the Summary Tables

- Energy Use
- Energy Supply
- CO2 Emissions

Look up the Data Tables

- Energy Use
- Energy Supply
- CO2 Emissions

4.2 Implementation as web tool

The implementation as a web tool offers the cascade structure of the energy system in an accessible way. The low access barriers allow especially stakeholders, but also other non-modelers, visualization and modification possibilities of all relevant information.

Users can create visions of the future of the Austrian energy system and all decisions are reflected in the composition of Energy Use, Energy Supply and induced CO_2 Emissions. The findings are visualized and can be compared with historic information.

The web tool is implemented as a responsive web application, which can be used on every contemporary computer, tablet and smartphone. All the chosen options are locally stored and remembered over multiple sessions. Two pages of the interface are illustrated in Figure 4-15 and Figure 4-16.

Figure 4-15 Visualization of Final Energy Consumption in 2050

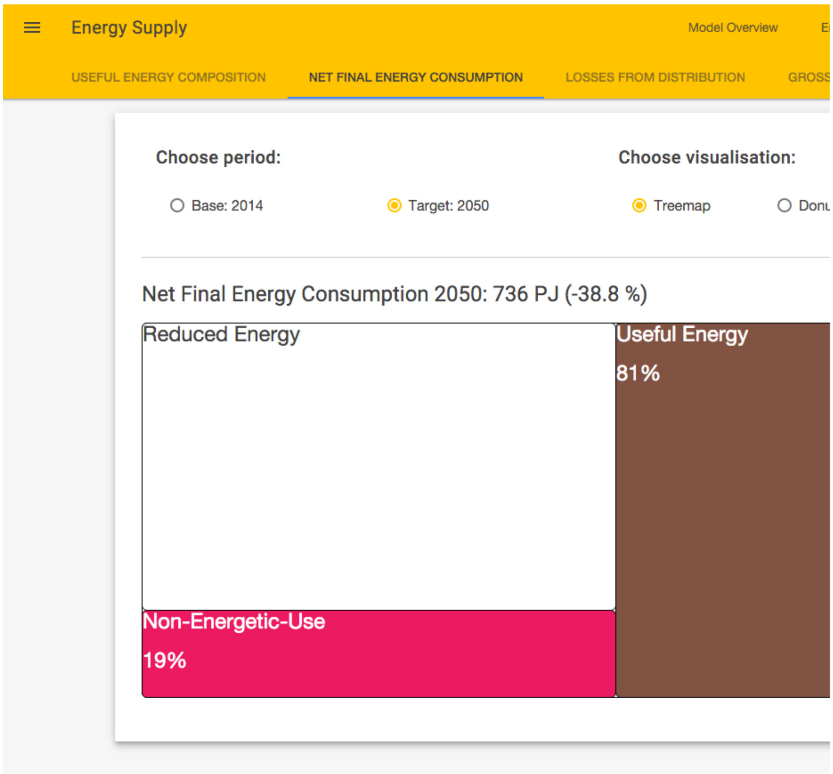
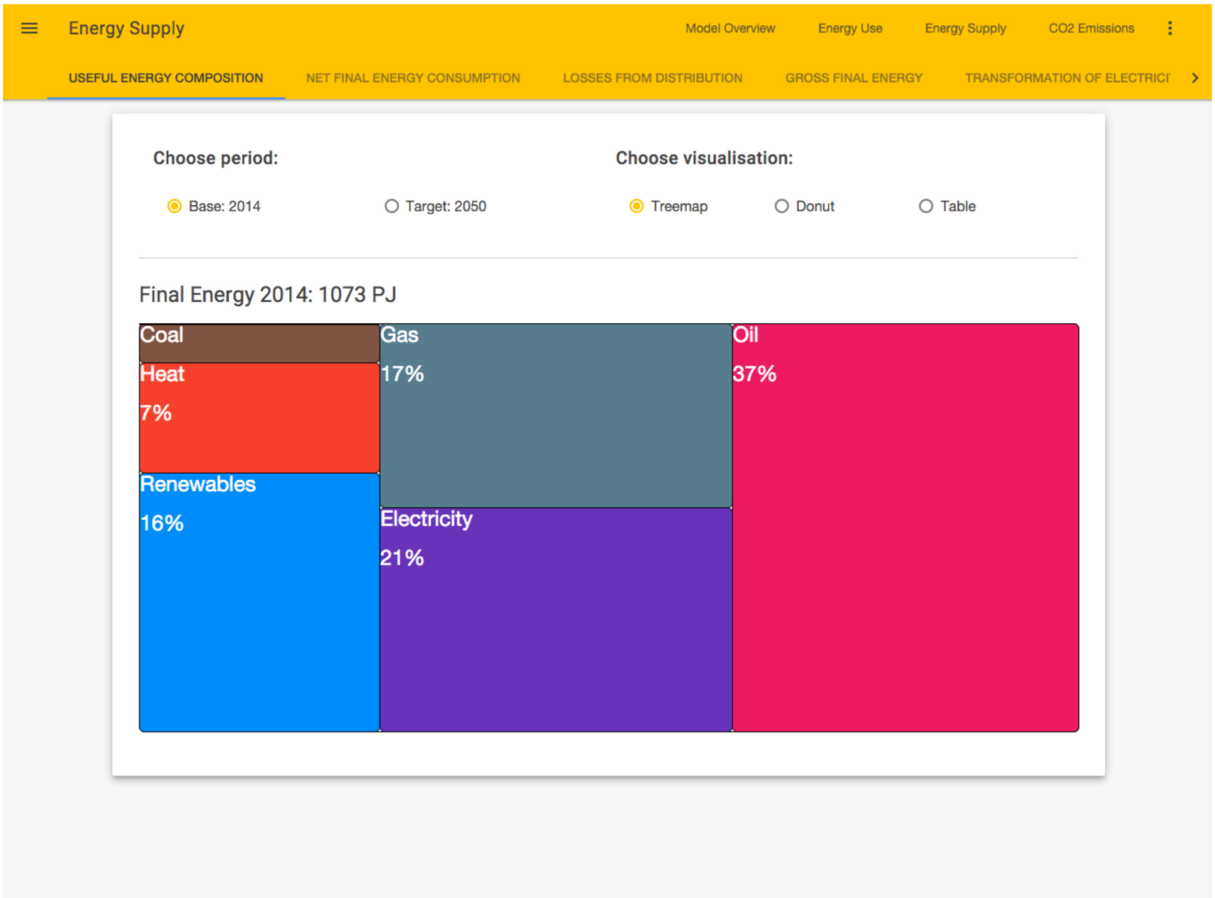


Figure 4-16 Visualization of Final Energy Consumption in 2014



5 A full scale energy model for Austria following the deepened structural modeling approach

5.1 Energy Use

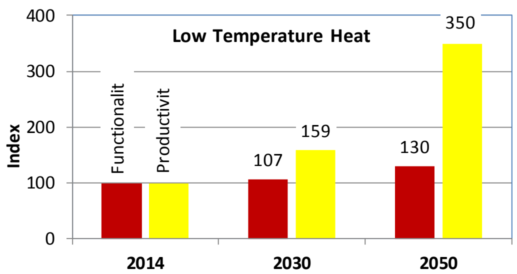
5.1.1 Functionalities and useful energy

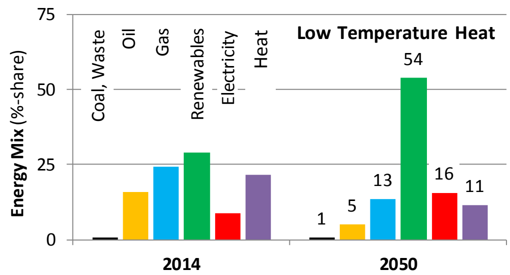
Low temperature heat

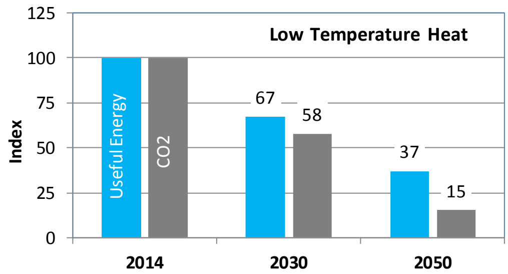
Table 5-3 *Low Temperature Heat*

Functionalities and Useful Energy					Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Low Temperature Heat	2014			*TJ*	**288,241**	2,031	46,037	70,410	83,032	24,960	61,770
		Functionality	Productivity			Start Period Energy Mix					
2014		*100*	*100*	*Index*	*100*	*1%*	*16%*	*24%*	*29%*	*9%*	*21%*
						Change of Energy Mix					
Change		*30*	*250*	*Index*	*-63*	*0%*	*-11%*	*-11%*	*25%*	*7%*	*-10%*
						End Period Energy Mix					
2050		*130*	*350*	*Index*	*37*	*1%*	*5%*	*13%*	*54%*	*16%*	*11%*
	2050			*TJ*	**107,061**	754	5,323	14,376	57,606	16,765	12,237

Figure 5-17 *Low Temperature Heat*





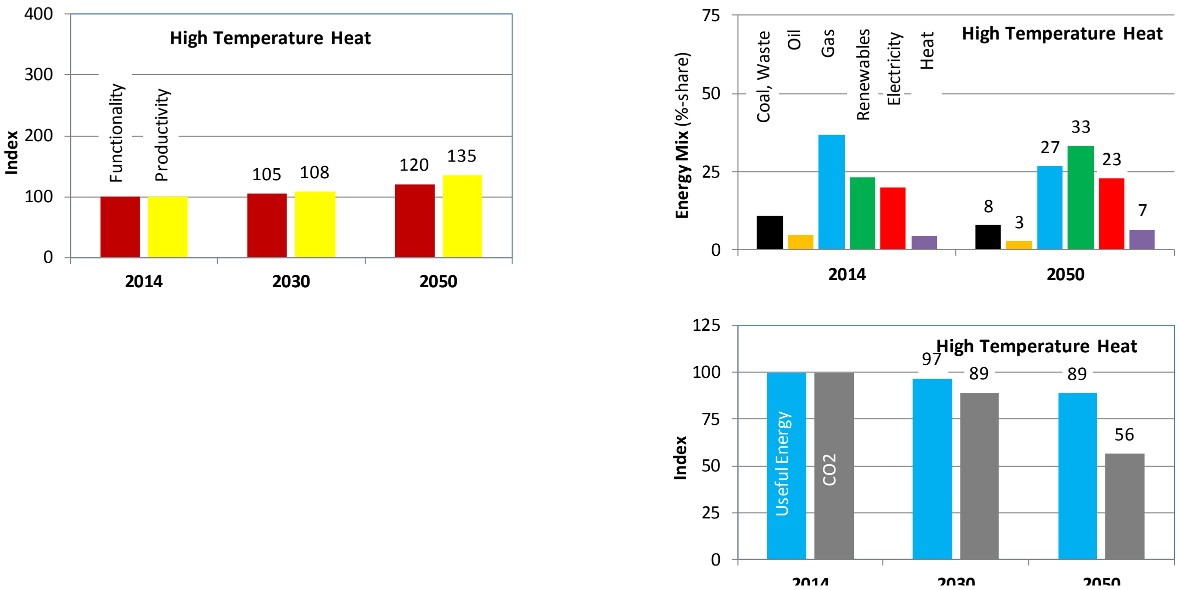


High temperature heat

Table 5-4 High Temperature Heat

Functionalities and Useful Energy				Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
High Temperature Heat		2014	TJ	**247,710**	26,940	11,741	90,899	57,707	49,243	11,180
	Functionality	Productivity			Start Period Energy Mix					
2014	*100*	*100*	*Index*	*100*	*11%*	*5%*	*37%*	*23%*	*20%*	*5%*
					Change of Energy Mix					
Change	*20*	*35*	*Index*	*-11*	*-3%*	*-2%*	*-10%*	*10%*	*3%*	*2%*
					End Period Energy Mix					
2050	*120*	*135*	*Index*	*89*	*8%*	*3%*	*27%*	*33%*	*23%*	*7%*
		2050	TJ	**220,187**	17,341	6,033	58,780	73,314	50,377	14,342

Figure 5-18 High Temperature Heat

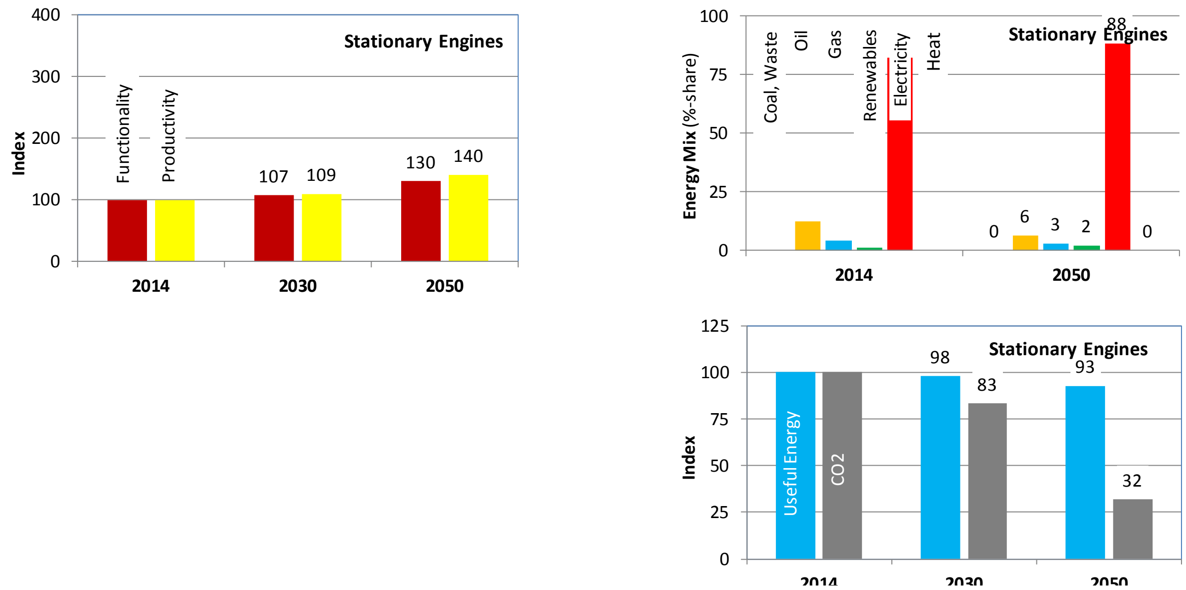


Stationary engines

Table 5-5 Stationary Engines

Functionalities and Useful Energy				Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Stationary Engines		2014	TJ	**119,843**	0	14,900	4,794	1,466	98,684	0
	Functionality	Productivity			Start Period Energy Mix					
2014	*100*	*100*	*Index*	*100*	*0%*	*12%*	*4%*	*1%*	*82%*	*0%*
					Change of Energy Mix					
Change	*30*	*40*	*Index*	*-7*	*0%*	*-6%*	*-1%*	*1%*	*6%*	*0%*
					End Period Energy Mix					
2050	*130*	*140*	*Index*	*93*	*0%*	*6%*	*3%*	*2%*	*88%*	*0%*
		2050	TJ	**111,283**	0	7,158	3,339	2,474	98,312	0

Figure 5-19 Stationary Engines

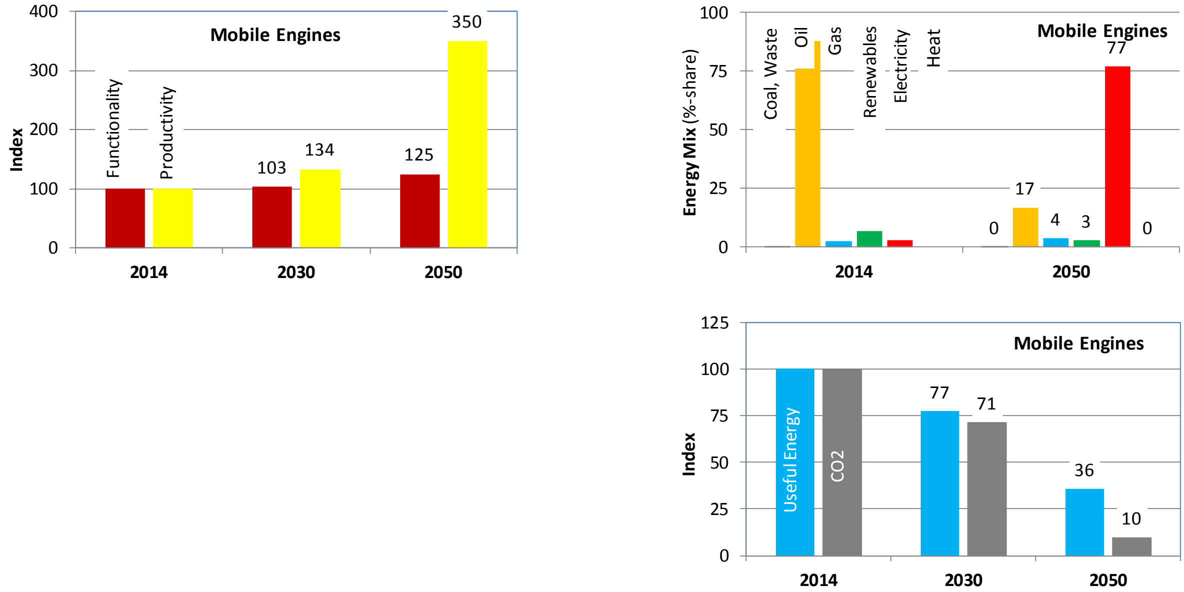


Mobile engines

Table 5-6 Mobile Engines

Functionalities and Useful Energy					Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Mobile Engines			2014	TJ	**376,036**	6	329,911	9,781	25,473	10,865	0
	Functionality	Productivity				Start Period Energy Mix					
2014	*100*	*100*		*Index*	*100*	*0%*	*88%*	*3%*	*7%*	*3%*	*0%*
						Change of Energy Mix					
Change	*25*	*250*		*Index*	*-64*	*0%*	*-71%*	*1%*	*-4%*	*74%*	*0%*
						End Period Energy Mix					
2050	*125*	*350*		*Index*	*36*	*0%*	*17%*	*4%*	*3%*	*77%*	*0%*
			2050	TJ	**134,299**	2	22,473	4,836	3,726	103,261	0

Figure 5-20 Mobile Engines

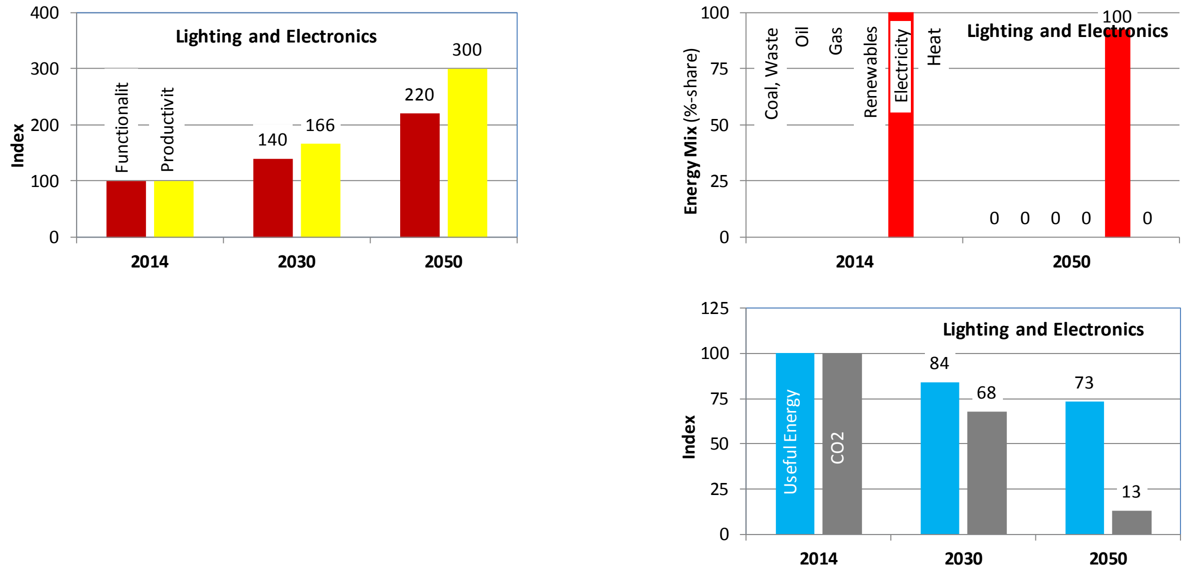


Lighting and electronics

Table 5-7 Lighting and Electronics

Lighting and Electronics		2014	*TJ*	**31,350**	0	0	0	0	31,350	0
	Functionality	Productivity			Start Period Energy Mix					
2014	*100*	*100*	*Index*	*100*	*0%*	*0%*	*0%*	*0%*	*100%*	*0%*
					Change of Energy Mix					
Change	*120*	*200*	*Index*	*-27*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
					End Period Energy Mix					
2050	*220*	*300*	*Index*	*73*	*0%*	*0%*	*0%*	*0%*	*100%*	*0%*
		2050	*TJ*	**22,990**	0	0	0	0	22,990	0

Figure 5-21 Lighting and Electronics

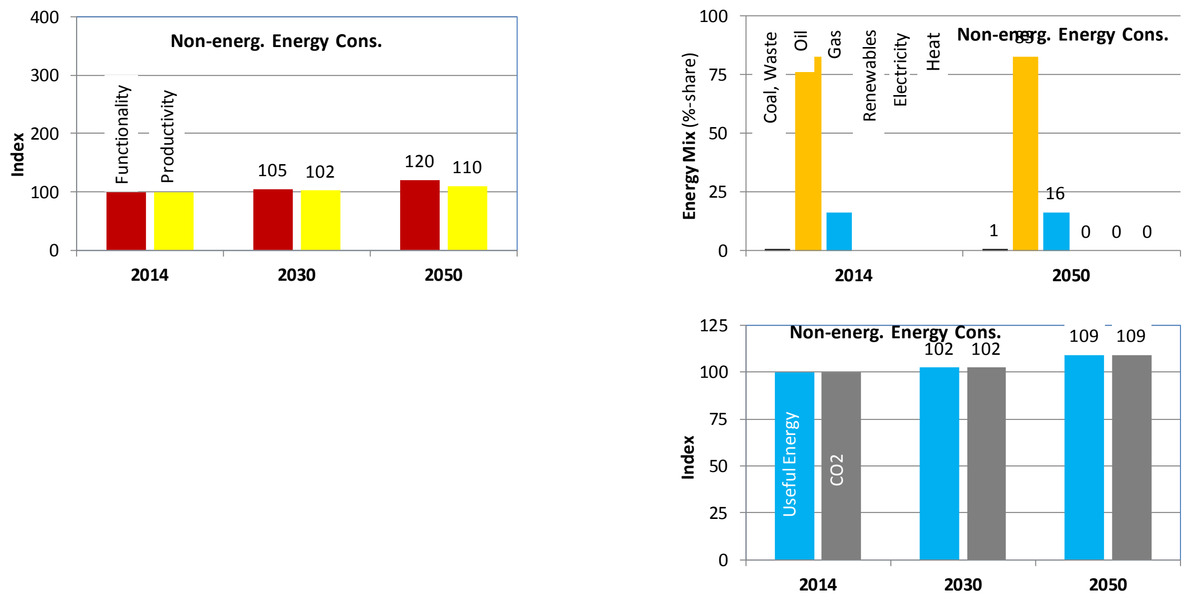


5.1.2 Non-energetic energy use

Table 5-8 Non-energetic Energy Use

Non-energetic Energy Use				Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Non-energetic Energy Use		2014	*TJ*	**84,944**	609	70,354	13,981	0	0	0
	Functionality	Productivity					*Start Period Energy Mix*			
2014	*100*	*100*	*Index*	*100*	*1%*	*83%*	*16%*	*0%*	*0%*	*0%*
							Change of Energy Mix			
Change	*20*	*10*	*Index*	*9*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
							End Period Energy Mix			
2050	*120*	*110*	*Index*	*109*	*1%*	*83%*	*16%*	*0%*	*0%*	*0%*
		2050	*TJ*	**92,666**	664	76,749	15,252	0	0	0

Figure 5-22 Non-energetic Energy Use



5.1.3 Summary Energy Use

Table 5-9 Final Energy Consumption

Final Energy Consumption		Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
2014	*TJ*	**1,063,181**	28,978	402,588	175,884	167,678	215,102	72,950
	Share		*3%*	*38%*	*17%*	*16%*	*20%*	*7%*
2050	*TJ*	**595,819**	18,098	40,987	81,331	137,119	291,706	26,579
	Share		*3%*	*7%*	*14%*	*23%*	*49%*	*4%*

Figure 9-23 Final Energy Consumption

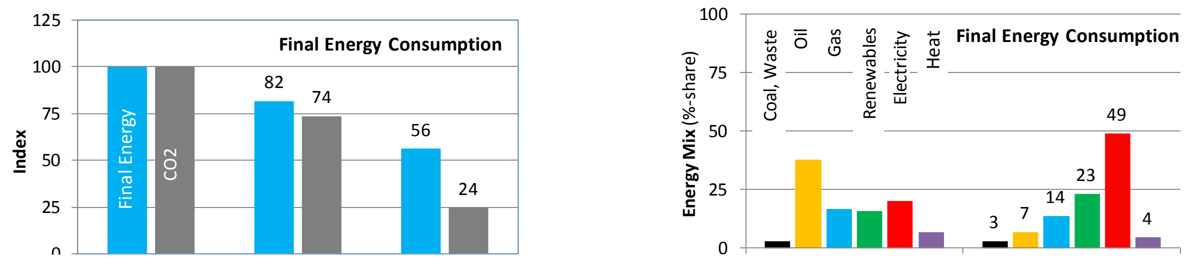


Table 5-10 Net Final Energy Consumption

Net Final Energy Consumption		Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
2014	*TJ*	**1,148,124**	29,587	472,942	189,865	167,678	215,102	72,950
	Share		*3%*	*41%*	*17%*	*15%*	*19%*	*6%*
2050	*TJ*	**688,485**	18,762	117,736	96,583	137,119	291,706	26,579
	Share		*3%*	*17%*	*14%*	*20%*	*42%*	*4%*

5.2 Energy supply

5.2.1 Energy distribution

Table 5-11 Losses from Distribution

Energy Distribution			Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Net Final Energy Cons.	*2014*	TJ	**1,148,124**	29,587	472,942	189,865	167,678	215,102	72,950
	2050	TJ	**688,485**	18,762	117,736	96,583	137,119	291,706	26,579
Losses from Distribution	*2014*	TJ	**148,570**	60,287	22,935	18,416	12	40,028	6,891
	2050	TJ	**67,837**	30,716	4,429	7,094	10	24,298	1,291
				Start Period Distribution Losses					
Shares of Disttribution Losses		%		*67%*	*5%*	*9%*	*0%*	*16%*	*9%*
				Change of Distribution Losses					
	Change	%		*-5%*	*-1%*	*-2%*	*0%*	*-8%*	*-4%*
				End Period Distribution Losses					
	2050	%		*62%*	*4%*	*7%*	*0%*	*8%*	*5%*
Gross Final Energy	*2014*	TJ	**1,296,695**	89,874	495,877	208,282	167,690	255,130	79,842
	2050	TJ	**756,322**	49,478	122,165	103,677	137,129	316,004	27,869

Table 5-12 Untransformed and Transformed Final Energy

Energy Distribution			Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Gross Final Energy	*2014*	TJ	**1,296,695**	89,874	495,877	208,282	167,690	255,130	79,842
	2050	TJ	**756,322**	49,478	122,165	103,677	137,129	316,004	27,869
Gross Final Energy Untransf.	*2014*	TJ	**522,597**	6,377	118,135	208,282	156,415	33,389	0
	2050	TJ	**265,918**	3,016	27,882	103,677	127,909	3,435	0
				Start Period Share of Untransformed Gross Final Energy					
Shares of Untransformed Gross Final Energy	*2014*	%		*7%*	*24%*	*100%*	*93%*	*13%*	*0%*
				Change of Share					
	Change	%		*-1%*	*-1%*	*0%*	*0%*	*-12%*	*0%*
				End Period Share of Untransformed Gross Final Energy					
	2050	%		*6%*	*23%*	*100%*	*93%*	*1%*	*0%*
Gross Final Energy Transf.	*2014*	TJ	**774,097**	83,497	377,742	0	11,276	221,741	79,842
	2050	TJ	**490,403**	46,462	94,283	0	9,221	312,568	27,869

5.2.2 Energy transformation

Table 5-13 *Transformation of Energy - Input Energy*

Energy Transformation			Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
			from	Coal, Waste	Oil	Gas	Biomass	Hydro	Wind, PV, …
Output Electricity	*2014*	*TJ*	**221,741**	20,157	2,192	19,442	15,619	147,608	16,723
				Start Period Input Shares for Electricity Generation					
Energy Mix for Electricity	*2014*	*Index*	*100*	*9%*	*1%*	*9%*	*7%*	*67%*	*8%*
				Change of Share					
	Change	*Index*	*41*	*-7%*	*-1%*	*-7%*	*-4%*	*-13%*	*32%*
				End Period Input Shares for Electricity Generation					
	2050	*Index*	*141*	*2%*	*0%*	*2%*	*3%*	*54%*	*40%*
	2050	*TJ*	**312,568**	6,534	276	5,213	9,514	167,436	123,595
			from	Coal, Waste	Oil	Gas	Biomass	Hydro	Wind, PV, …
Output Heat	*2014*	*TJ*	**79,842**	9,022	3,920	30,703	35,592	0	604
				Start Period Input Shares for Heat Generation					
Energy Mix for Heat	*2014*	*Index*	*100*	*11%*	*5%*	*38%*	*45%*	*0%*	*1%*
				Change of Share					
	Change	*Index*	*-65*	*-2%*	*-3%*	*-17%*	*11%*	*0%*	*11%*
				End Period Input Shares for Heat Generation					
	2050	*Index*	*35*	*9%*	*2%*	*21%*	*56%*	*0%*	*12%*
	2050	*TJ*	**27,869**	2,592	532	5,979	15,489	0	3,277
			from	Coal, Waste	Oil	Gas	Biomass		
Output Other Transform.	*2014*	*TJ*	**472,515**	83,497	377,742	0	11,276		
	2050	*TJ*	**149,965**	46,462	94,283	0	9,221		

Table 5-14 *Transformation of Energy – Transformation Losses*

Energy Transformation			**Total**	**Coal, Waste**	**Oil**	**Gas**	**Renewables**	**Electricity**	**Heat**
			from	Coal, Waste	Oil	Gas	Biomass	Hydro	Wind, PV, …
Losses from E & H Transf.	*2014*	*TJ*	**78,877**	32,422	2,399	11,406	32,651	0	0
	2050	*TJ*	**22,941**	7,356	258	1,903	13,424	0	0
				Start Period Electricity and Heat Transformation Losses					
Share of Transformat. Losses	*2014*	%		*53%*	*28%*	*19%*	*39%*	*0%*	*0%*
in Electricity and Heat Processes				Change of Distribution Losses					
	Change	%		*-8%*	*-4%*	*-4%*	*-4%*	*0%*	*0%*
				End Period Electricity and Heat Transformation Losses					
	2050	%		*45%*	*24%*	*15%*	*35%*	*0%*	*0%*
Input Electricity and Heat	*2014*	*TJ*	**380,460**	61,601	8,511	61,551	83,861	147,608	17,327
	2050	*TJ*	**363,379**	16,482	1,066	13,096	38,427	167,436	126,871

				Coal, Waste	Oil	Gas	Biomass
Losses from Other Transf.	*2014*	*TJ*	**5,239**	4,203	874	0	162
	2050	*TJ*	**2,323**	2,323	0	0	0
Input Other Transformations	*2014*	*TJ*	**477,754**	87,700	378,616	0	11,438
	2050	*TJ*	**152,288**	48,785	94,283	0	9,221

			Total	**Coal, Waste**	**Oil**	**Gas**	**Biomass**	**Hydro**	**Wind, PV, …**
Input Transformation	*2014*	*TJ*	**858,213**	149,301	387,127	61,551	95,299	147,608	17,327
	2050	*TJ*	**515,668**	65,267	95,349	13,096	47,648	167,436	126,871

Table 5-15 *Gross Energy Supply*

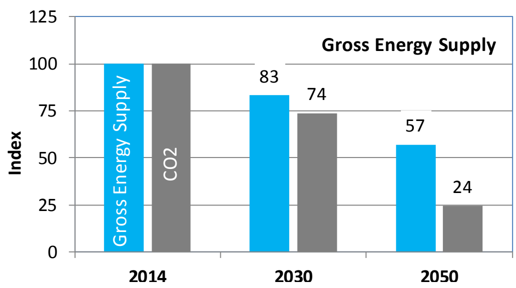
Gross Energy Supply		**Total**	**Coal, Waste**	**Oil**	**Gas**	**Renewables**	**Electricity**	**Heat**
2014	*TJ*	**1,380,811**	155,678	505,262	269,832	416,649	33,389	0
	Share		*11%*	*37%*	*20%*	*30%*	*2%*	*0%*
2050	*TJ*	**781,586**	68,283	123,232	116,772	469,864	3,435	0
	Share		*9%*	*16%*	*15%*	*60%*	*0%*	*0%*

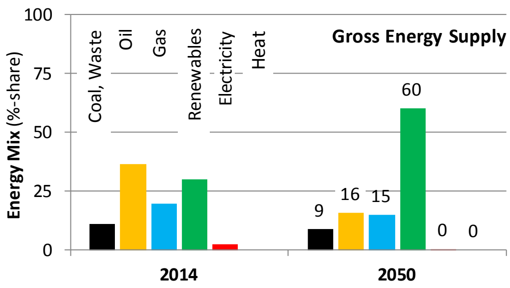
5.2.3 Summary Energy Supply

Table 5-16 *Summary Energy Supply*

Energy Supply			Total	Coal, Waste	Oil	Gas	Renewables	Electricity	Heat
Net Final Energy Cons.	*2014*	*TJ*	**1,148,124**	29,587	472,942	189,865	167,678	215,102	72,950
	2050	*TJ*	**688,485**	18,762	117,736	96,583	137,119	291,706	26,579
Losses from Distribution	*2014*	*TJ*	**148,570**	60,287	22,935	18,416	12	40,028	6,891
	2050	*TJ*	**67,837**	30,716	4,429	7,094	10	24,298	1,291
Gross Final Energy	*2014*	*TJ*	**1,296,695**	89,874	495,877	208,282	167,690	255,130	79,842
	2050	*TJ*	**756,322**	49,478	122,165	103,677	137,129	316,004	27,869
Gross Final Energy Untransf.	*2014*	*TJ*	**522,597**	6,377	118,135	208,282	156,415	33,389	0
	2050	*TJ*	**265,918**	3,016	27,882	103,677	127,909	3,435	0
Gross Final Energy Transf.	*2014*	*TJ*	**774,097**	83,497	377,742	0	11,276	221,741	79,842
	2050	*TJ*	**490,403**	46,462	94,283	0	9,221	312,568	27,869
Losses from Transformations	*2014*	*TJ*	**84,116**	36,625	3,273	11,406	32,813	0	0
	2050	*TJ*	**25,265**	9,680	258	1,903	13,424	0	0
Gross Energy Supply	2014	*TJ*	**1,380,811**	155,678	505,262	269,832	416,649	33,389	0
		Share		*11%*	*37%*	*20%*	*30%*	*2%*	*0%*
	2050	*TJ*	**781,586**	68,283	123,232	116,772	469,864	3,435	0
		Share		*9%*	*16%*	*15%*	*60%*	*0%*	*0%*

Figure 5-24 *Gross Energy Supply*



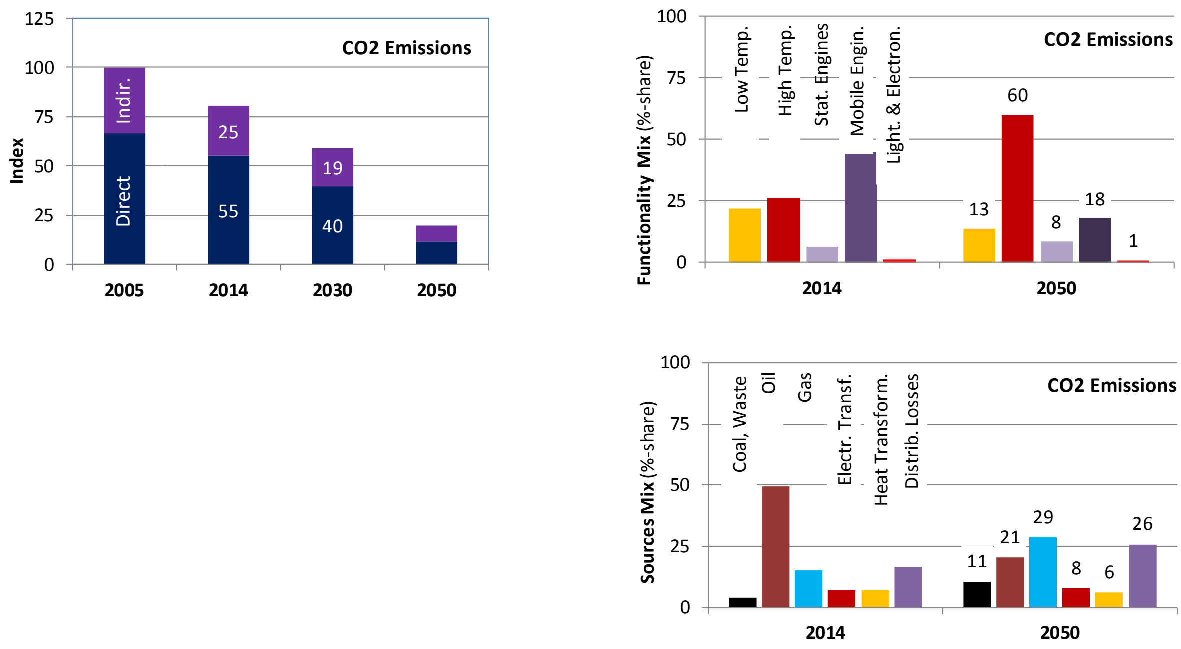


5.3 CO_2 Emissions from Energy Use

Table 5-17 *CO_2 Emissions from Energy Use*

CO2 Emissions			Total	Coal, Waste	Oil	Gas	Electricity	Heat	Distribution
				Direct Emissions			Indirect Emissions		
Low temperature heat	2014	*thsd t*	**13,796**	187	3,591	3,873	535	3,840	1,771
	2005	*Index*	*100*	Start Period Distribution					
	2014	*Index*	*67*	*1%*	*26%*	*28%*	*4%*	*28%*	*13%*
	2030	*Index*	*42*	End Period Distribution					
	2050	*Index*	*10*	*3%*	*20%*	*38%*	*3%*	*21%*	*15%*
	2050	*thsd t*	**2,098**	69	415	791	71	439	313
High temperature heat	2014	*thsd t*	**16,500**	2,479	916	4,999	1,055	695	6,356
	2005	*Index*	*100*	Start Period Distribution					
	2014	*Index*	*87*	*15%*	*6%*	*30%*	*6%*	*4%*	*39%*
	2030	*Index*	*79*	End Period Distribution					
	2050	*Index*	*49*	*17%*	*5%*	*35%*	*2%*	*6%*	*35%*
	2050	*thsd t*	**9,308**	1,595	471	3,233	213	514	3,282
Stationary Engines	2014	*thsd t*	**4,059**	0	1,162	264	2,115	0	518
	2005	*Index*	*100*	Start Period Distribution					
	2014	*Index*	*69*	*0%*	*29%*	*6%*	*52%*	*0%*	*13%*
	2030	*Index*	*59*	End Period Distribution					
	2050	*Index*	*22*	*0%*	*43%*	*14%*	*32%*	*0%*	*10%*
	2050	*thsd t*	**1,290**	0	558	184	415	0	133
Mobile Engines	2014	*thsd t*	**28,372**	1	25,733	538	233	0	1,868
	2005	*Index*	*100*	Start Period Distribution					
	2014	*Index*	*89*	*0%*	*91%*	*2%*	*1%*	*0%*	*7%*
	2030	*Index*	*67*	End Period Distribution					
	2050	*Index*	*9*	*0%*	*64%*	*10%*	*16%*	*0%*	*11%*
	2050	*thsd t*	**2,754**	0	1,753	266	436	0	299
Lighting and Electronics	2014	*thsd t*	**797**	0	0	0	672	0	125
	2005	*Index*	*100*	Start Period Distribution					
	2014	*Index*	*50*	*0%*	*0%*	*0%*	*84%*	*0%*	*16%*
	2030	*Index*	*36*	End Period Distribution					
	2050	*Index*	*7*	*0%*	*0%*	*0%*	*92%*	*0%*	*8%*
	2050	*thsd t*	**105**	0	0	0	97	0	8
CO2 from Energy Use	2014	*thsd t*	**63,524**	2,666	31,402	9,674	4,610	4,535	10,637
	2005	*Index*	*100*	Start Period Distribution					
	2014	*Index*	*80*	*4%*	*49%*	*15%*	*7%*	*7%*	*17%*
	2030	*Index*	*62*	End Period Distribution					
	2050	*Index*	*20*	*11%*	*21%*	*29%*	*8%*	*6%*	*26%*
	2050	*thsd t*	**15,555**	1,665	3,197	4,473	1,232	953	4,035

Figure 5-25 CO_2 Emissions from Energy Use



6 Lessons that might be worth learning

We summarize now some key issues that were developed in this handbook for a deepened structural approach to energy modeling.

6.1 Mind your mindset

The need for a next generation of energy models

There are many reasons for initiating a major joint research effort to switch to a next generation of energy models, above all the emerging breakthrough-technologies, the promising options for a transition to low-energy and low-carbon energy systems, and the accompanying far reaching changes in the business and institutional environments.

The accompanying keywords: inversion, innovation, and integration

For model-based analyses this means switching to a mindset that can be characterized by three keywords:

Inversion
: of the reasoning by focusing first on the functionalities expected from an energy system and sequel on the options for providing these functionalities by a careful selection of technologies and energy flows.

Innovation
: of all facets of the emerging energy systems of the future, ranging from energy-autonomous buildings to new materials and processes for products and the new storage systems for electricity that may not before long change transport and electricity grids.

Integration
: of all components that constitute the infrastructure and energy flows for providing a specific functionality for thermal, mechanical and specific electric services.

Deepened structural modeling frameworks for a better understanding of energy systems

An obvious answer to these new challenges is the opening of the black box of conventional energy models by indulging into a deepened structural modeling framework that explicitly deals the following components:

The energy system
: is described by an in depth specification of the physical structure, starting with functionalities and continuing with application and transformation technologies that finally determine the volume and the mix of energy flows.

The economic system
: with the linkages between the energy and non-energy sector and the impacts of innovations on energy flows and capital stocks.

The institutional system
: which governs the coordination by markets and regulation but is also concerned with incentives for changing behavioral attitudes and innovations for technologies and business models.

Basic virtues of scientific honesty

Also in this innovative modeling framework, some basic virtues of scientific honesty need to be observed:

Be honest and open about your model's assumptions and how they are driving the results and hence potential policy suggestions

Make yourself clear that your model is based on normative assumptions and your personal cultural context and worldviews.

Even though economic and energy modelers often perceive their research as purely positivistic, the basic assumptions underlying their models already lead to certain normative conclusions, e.g. regarding distributional justice issues; substitutability of natural capita with human-made capital; the role of labor unions; free market supremacy.

6.2 A checklist for evaluating energy models

This checklist addresses energy models which are intended to serve a better understanding of the long-term transition that has already started in our energy systems.

Given this aim, we want to obtain better insights into the enormous potential for innovation with the help of an analytical modeling framework. Without wanting to be too simplistic we identify three types of intellectual contributions with respect to the modeling designs: essential, experimental and expired.

Essential

If we can agree that for many reasons fundamental transitions of the energy systems are unavoidable and require a deepened understanding of their structures and their driving mechanisms, then we also need to agree on some essential elements in the modeling designs.

Functionalities

The fulfillment of thermal, mechanical and specific electric functionalities or energy services is the ultimate task of any energy system. Although we need better databases about these functionalities, there are operational procedures for dealing with them in a modeling framework.

Technologies

Transitions in our energy systems are closely tied to technological changes, some of them are going to be disruptive for existing structures. A minimal requirement is to deal explicitly with application technologies for providing functionalities and with transformation technologies that convert primary to final energy flows.

Capital stocks

Capital stocks, from buildings to vehicles, from railway tracks to the internet and from heat pumps powered by photovoltaics to micro grids, are the decisive infrastructure that determines the transition to innovative structures of the energy system. Similarly the institutions and societies´ implicit and explicit socio-institutional “capital stock” are the decisive social infrastructure that eases or hinders the transition to innovative structures of the energy system.

Both the quality and the quantity of both physical and institutional capital stock adjustments need to be explicatively modeled.

Separation of system

Any transitions in our energy systems are reflected in changes of their

structures from driving mechanisms

structures which in turn are described in the way functionalities are provided and energy is transformed. These changes may be driven by different mechanisms, from building standards to energy taxes, from co-design to participatory approaches, and therefore should be separated in the modeling design.

Experimental

Deepened structural modeling approaches reveal the needs for a much better understanding of the linkages between the energy and the economic system, which in turn is governed by the institutional setup for markets, regulations and incentives.

Far from being able to give proven answers, we want to emphasize putting questions that emerge in a deepened structural modeling framework.

What interaction with the socio-economic system

The interactions between the energy and the economic system concern on the one hand the flow of energy for operating and on the other hand the investments in the capital stock for application and transformation technologies that provide the infrastructure of the energy system. This differentiation and its implication for providing the functionalities of the energy system need to be further explored.

What competition

The conventional understanding of competition is mostly limited to single types of energy, as oil and gas or electricity and heat. A comprehensive understanding of the energy system recommends installing markets for providing energy related functionalities, as keeping buildings over the whole year at comfortable temperatures or moving persons and goods over local, regional or transnational distances. Thus limiting competition in energy models to seemingly isolated markets for single types of energy, as for crude oil or electricity, will not be sufficient.

What incentives

There is a lot more to be said about incentives than just recommending monetary transfers. Investments in buildings e.g., can be improved by installing adequate financial vehicles that extend the length of mortgages or switching to public transport can be encouraged to a more sophisticated ticketing system. By emphasizing for the design of incentives a system point of view, recommendations for stimulating transitions of the energy system mainly by a CO_2 tax will turn out to be just too simplistic. Such an analysis, however, needs also an adequate modeling framework.

What innovation

Envisioned transitions of our energy system to low-energy and low-carbon structures recommend targeted innovation policies. There is a unique opportunity to encourage emerging breakthrough-technologies, as a new generation of electricity storage, and to integrate these technologies into the energy system. This is another motivation for a deepened structural modeling specification.

What business models

Closely tied to the emerging transitions of our energy systems are new business models that focus on serving the functionalities than selling energy flows. Similarly we observe for capital goods, like cars, a shift from ownership to use and a corresponding reorientation of the business models. The next generation of model designs should be able to handle also this transition.

Expired

Without wanting to add insult to injury we list some common practices in energy modeling which definitely have reached an expiration date.

Implausible assumptions about causalities

Neither relevant nor predictable are a long list of variables that misleadingly still show up in many models as drivers for long-term energy structures: economic activity as GDP (from which we want decouple energy flows), energy prices as those for oil, gas, coal and carbon allowances (since we are going to deal with disruptive changes) or even exchange rates (because of the volatility of the financial markets).

Specifications based on irreproducible parameters

Closely tied with implausible causalities are the corresponding elasticities for economic activities and prices which either need a lot of prior restrictions in order to match with a historical database or might lack any evidence check with current behavior as elasticities of substitution in nested production functions.

Claims of forecasting capabilities

Economics was caught by surprise to engage in policy issues with time ranges up to the year 2100 and beyond. It will still take some time to obtain a mutual understanding what the contribution of economics could be in long-term issues. For sure it will be not the pretention of being able to provide forecasts, either unconditional or seemingly safer when based on conditions.

Prices resulting from market equilibria

Although prices seem to be the main mechanism that drives day-to-day decisions, this is only partially true for the consumption of energy goods, like electricity and fuels, let alone for investment decisions concerning buildings and cars. Even more debatable is the claim that observed prices reflect market equilibria.

Scenarios based on input-output tables

Input-output tables reveal a lot about the value chains and interactions between economic sectors. Given the emerging changes in the design of products, in the organization of production process and the role of new materials, it is just not reasonable to make sectoral projections based on input-output tables over time spans that are relevant for the transformations of the energy and other sectors of our economies.

Impact analyses based on computable general equilibrium models

Although energy models, which are characterized by computable general equilibrium specifications, have become very appealing from the point of view of economic theory and seemingly useful for answering many policy questions, there is an emerging understanding that these models if used without complementary analysis lack many required capabilities for dealing with long-term transition processes.

Separate strategies for single types of energy

Both on a European and on national scales separate energy strategies, e.g. for electricity, heat and renewables, have emerged. These strategies neglect in an integrated system perspective potential incompatibilities with functionalities and potential innovations in application and transformation technologies.

PRIMES scenarios for Europe

The PRIMES modeling framework should not be used anymore for predictive statements about the future of the European energy system or for impact analyses, e.g. for carbon prices. The main virtue of the current PRIMES model is a comprehensive and coherent database that could be a good starting point for deepened structural specifications of the current modeling framework.

WEM and WAM scenarios for Austria

Energy scenarios with time ranges up to 2050 have become available for Austria under the heading “with existing measures (WEM)” and “with additional measures (WAM)”. Both the pretense of being able to predict and differentiate policy impacts over such time spans without explicitly reporting sensitivity on the crucial assumptions without explicitly reporting sensitivity on the crucial assumptions used not is justified.

6.3 Naming without shaming

The mindset of economists and economics is closely related to modeling as Leijonhufvud (1973) pointed out in his sharp-witted and up to today valid satire. In fact, economics is perhaps more than any other social science model-oriented and there are many reasons for this, e.g. the history of the discipline with ideas coming from the natural sciences (particularly Newtonian physics), the search for universality, mathematical rigor and precision.

We conclude therefore with commenting three familiar modeling approaches which might serve as benchmarks for further discussions about deepened structural modeling in the context of energy.

6.3.1 Hidden and critical assumptions of the PRIMES model

Lack of transparency and debatable assumptions

Over many years if not decades the PRIMES model (E3mlab, 2015) has become a kind of workhorse for evaluating impacts of almost all energy related European policy decisions.

This practice, however, has come under critical attacks, mainly articulating complaints about a lack of transparency regarding the general model structure as well as the choice of critical assumptions.

As an example of such critical assumptions might serve a dispute about the values of GDP up to 2050, which serve as an important exogenous input to the PRIMES model and a key driver of modeling results. It was revealed (European Commission, 2016) that these values were taken from the 2015 Aging Report (European Commission, 2015).

This practice contains at least two major flaws: First, it is absolutely impossible to make statements about GDP with any predictive power just beyond one year, as forecasting performance over recent years confirms; second there are many reasons that GDP will not be a relevant driver for energy use before long if we really want to decouple energy flows from GDP, which will be essential for achieving any low-carbon targets.

Despite these and other similar flaws in the model design for which PRIMES is representative, many policy impact analyses of the European Commission claim using well-founded in economic theory by referring to these type of models. Since opening the black box of e.g. the PRIMES model reveals a kind of emperor's new clothes effect, it is highly recommended to reflect more critically on modeling results and derived policy suggestions that are argued with these models. Finally this might be a good time for phasing out the use of conventional energy models and substituting them with deepened structural modeling approaches in particular when long-term transitions are concerned.

6.3.2 Scrutinizing the energy scenarios of Umweltbundesamt Wien

Renewable energy scenarios for Austria

More details about the modeling of energy scenarios are provided in a research report by Umweltbundesamt Wien (2016) in their analysis of renewable energy scenarios for Austria.

Table 6-18 lists key input parameters used for producing scenarios under the heading WEM ("with existing measures") and WAM "(with additional plus measures").

Table 6-18 *Inputs used for modeling WEM (with existing measures) and WAM (with additional plus measures) scenarios*

Inputs for WEM and WAM plus scenarios	2010	2020	2030	2040	2050
GDP (bill € 2010)	285	330	383	441	495
Population (mill persons)	8.382	8.733	9.034	9.277	9.46
Places of residence (mill)	3.62	3.86	4.05	4.17	4.25
Heating degree days	3,252	3,204	3,118	3,013	2,907
Exchange rate USD/€	1.33	1.30	1.30	1.30	1.30
International price for coal (USD 2010 / ton)	99.2	109.0	116.0	156.0	197.0
International price for oil (USD 2010)	78.1	148.0	212.0	267.0	335.0
International price for oil (USD 2010 / bbl)	78.1	118.0	135.0	139.0	143.0
International price for gas (USD 2010 / GJ)	7.1	10.4	11.9	13.1	14.3
Price for CO_2 allowances (€ 2010 / ton CO_2) WEM	13	20	30	78	100
Price for CO_2 allowances (€ 2010 / ton CO_2) WAM plus	13	20	35	87	162

Source: Umweltbundesamt (2016)

Having a detailed look at this table can be quite revealing and might lead to questioning the credibility of the underlying and many similar modeling exercises. First, although the exogenous input parameters listed in this table might be needed in the current mainstream modeling mindset, there is mounting reasoning, as explains in this paper, that this paradigm has limited relevance for developing real-world energy policies for time ranges up to 2050. Secondly, not even for 2020 can the variables in this table claim any predictive power. Third, it is just impossible to discriminate between the specified policies labeled "with existing measures" (WEM) and "with additional plus measures" (WAM plus).

Thus modeling exercises that rely on assumption as listed in *Table 6-18* serve as a benchmark for two types of misconceptions: wrong questions that just should not be put and misleading answers that just should not be given. The inertia with respect to changing paradigms will be measured by the time it will take to abandon the WEM and WAM vocabulary.

6.3.3 A ministry's view on the energy perspectives of WIFO and Wegener Center

Long-term energy perspectives for Austria

The Austrian Federal Ministry of Science, Research and Economy commissioned to the Austrian Institute of Economic Research (WIFO) and the Wegener Center at the University of Graz a research project on a long-term view of the Austrian energy system, which is reported in Köppl and Schleicher (2014). Surprisingly, the Ministry added on its website a remark to this report, stating that the results and the methodology of this work do not correspond with similar projects commissioned by the Ministry and based on that questioned if this is a realistic approach to analyzing energy systems.

Deliberately labelled as energy perspectives and not energy scenarios for Austria, this research project closely follows the deepened structural modeling approach by using the sGAIN modeling family. The fact that the innovative mindset and the related methodological approach did not obtain a supporting echo by the sponsoring Ministry might be interpreted as a kind of Litmus test for institutional barriers that hamper a progressive energy policy.

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8 Appendix 1: Dan Rodik’s Ten Commandments for economists and non-economists

These are the recommendations of Dan Rodik (2015) with respect to economic modeling.

Ten Commandments for economists

(1) Economics is a collection of models; cherish their diversity.

(2) It’s a model, not the model.

(3) Make your model simple enough to isolate specific causes and how they work, but not so simple that it leaves out key interactions among causes.

(4) Unrealistic assumptions are OK; unrealistic critical assumptions are not OK.

(5) The world is (almost) always second best.

(6) To map a model to the real world you need explicit empirical diagnostics, which is more craft than science.

(7) Do not confuse agreement among economists for certainty about how the world works.

(8) It’s OK to say “I don’t know” when asked about the economy or policy.

(9) Efficiency is not everything.

(10) Substituting your values for the public’s is an abuse of your expertise.

Ten commandments for non-economists

(1) Economics is a collection of models with no predetermined conclusions; reject any arguments otherwise.

(2) Do not criticize an economist's model because of its assumptions; ask how the results would change if certain problematic assumptions were more realistic.

(3) Analysis requires simplicity; beware of incoherence that passes itself off as complexity.

(4) Do not let math scare you; economists use math not because they're smart, but because they're not smart enough.

(5) When an economist makes a recommendation, ask what makes him/her sure the underlying model applies to the case at hand.

(6) When an economist uses the term "economic welfare," ask what he / she means by it.

(7) Beware that an economist may speak differently in public than in the seminar room.

(8) Economists don't (all) worship markets, but they know better how they work than you do.

(9) If you think all economists think alike, attend one of their seminars.

(10) If you think economists are especially rude to noneconomists, attend one of their seminars.

9 Appendix 2: Key data of the Austrian energy system and perspectives up to 2050

9.1 Energy Use

Table 9-19 Functionalities and related Useful Energy

TJ	2005	2014	2020	2030	2040	2050
Useful Energy	**1,102,661**	**1,063,181**	**1,037,759**	**893,307**	**636,860**	**595,819**
Low Temperatur Heat	327,421	288,241	274,981	205,314	115,860	107,061
High Temperature Heat	251,624	247,710	246,897	240,951	223,404	220,187
Stationary Engines	103,494	119,843	119,581	117,683	112,252	111,283
Mobile Engines	389,332	376,036	365,683	302,439	162,083	134,299
Lighting and Electronigs	30,789	31,350	30,618	26,921	23,261	22,990
Low Temperatur Heat	327,421	288,241	274,981	205,314	115,860	107,061
Coal and Waste	*4,856*	*2,031*	*1,938*	*1,447*	*816*	*754*
Oil	*90,729*	*46,037*	*43,252*	*28,404*	*7,692*	*5,323*
Gas	*83,855*	*70,410*	*66,504*	*45,765*	*17,489*	*14,376*
Renewables	*69,858*	*83,032*	*80,729*	*69,117*	*57,950*	*57,606*
Electricity	*30,546*	*24,960*	*24,237*	*20,572*	*16,914*	*16,765*
Heat	*47,577*	*61,770*	*58,321*	*40,009*	*14,999*	*12,237*
High Temperature Heat	251,624	247,710	246,897	240,951	223,404	220,187
Coal and Waste	*29,355*	*26,940*	*26,688*	*24,801*	*18,611*	*17,341*
Oil	*20,792*	*11,741*	*11,594*	*10,484*	*6,798*	*6,033*
Gas	*103,080*	*90,899*	*90,055*	*83,737*	*63,025*	*58,780*
Renewables	*46,696*	*57,707*	*58,062*	*60,814*	*70,999*	*73,314*
Electricity	*45,523*	*49,243*	*49,244*	*49,303*	*50,097*	*50,377*
Heat	*6,177*	*11,180*	*11,253*	*11,811*	*13,874*	*14,342*
Stationary Engines	103,494	119,843	119,581	117,683	112,252	111,283
Coal and Waste	*0*	*0*	*0*	*0*	*0*	*0*
Oil	*16,511*	*14,900*	*14,709*	*13,259*	*8,242*	*7,158*
Gas	*785*	*4,794*	*4,757*	*4,479*	*3,538*	*3,339*
Renewables	*2*	*1,466*	*1,489*	*1,668*	*2,325*	*2,474*
Electricity	*86,196*	*98,684*	*98,627*	*98,277*	*98,147*	*98,312*
Heat	*0*	*0*	*0*	*0*	*0*	*0*
Mobile Engines	389,332	376,036	365,683	302,439	162,083	134,299
Coal and Waste	*10*	*6*	*6*	*5*	*3*	*2*
Oil	*368,097*	*329,911*	*317,550*	*241,471*	*63,082*	*22,473*
Gas	*6,545*	*9,781*	*9,558*	*8,203*	*5,330*	*4,836*
Renewables	*2,317*	*25,473*	*24,587*	*19,143*	*6,522*	*3,726*
Electricity	*12,363*	*10,865*	*13,982*	*33,617*	*87,145*	*103,261*
Heat	*0*	*0*	*0*	*0*	*0*	*0*
Lighting and Electronics	30,789	31,350	30,618	26,921	23,261	22,990
Coal and Waste	*0*	*0*	*0*	*0*	*0*	*0*
Oil	*0*	*0*	*0*	*0*	*0*	*0*
Gas	*0*	*0*	*0*	*0*	*0*	*0*
Renewables	*0*	*0*	*0*	*0*	*0*	*0*
Electricity	*30,789*	*31,350*	*30,618*	*26,921*	*23,261*	*22,990*
Heat	*0*	*0*	*0*	*0*	*0*	*0*

Table 9-20 *Final Energy*

TJ	2005	2014	2020	2030	2040	2050
Final Energy Consumption	**1,102,661**	**1,063,181**	**1,037,759**	**893,307**	**636,860**	**595,819**
Coal and Waste	34,222	28,978	28,632	26,253	19,430	18,098
Oil	496,129	402,588	387,104	293,619	85,814	40,987
Gas	194,265	175,884	170,874	142,184	89,382	81,331
Renewables	118,873	167,678	164,868	150,742	137,796	137,119
Electricity	205,418	215,102	216,707	228,690	275,564	291,706
Heat	53,754	72,950	69,574	51,821	28,873	26,579
Non-energetic Energy Consumption	**73,859**	**84,944**	**85,131**	**86,562**	**91,587**	**92,666**
Coal and Waste	496	609	610	620	656	664
Oil	60,162	70,354	70,508	71,694	75,856	76,749
Gas	13,200	13,981	14,012	14,248	15,075	15,252
Renewables	0	0	0	0	0	0
Electricity	0	0	0	0	0	0
Heat	0	0	0	0	0	0
Net Final Energy	**1,176,520**	**1,148,124**	**1,122,890**	**979,870**	**728,447**	**688,485**
Coal and Waste	34,718	29,587	29,242	26,873	20,086	18,762
Oil	556,291	472,942	457,612	365,313	161,670	117,736
Gas	207,466	189,865	184,886	156,431	104,457	96,583
Renewables	118,873	167,678	164,868	150,742	137,796	137,119
Electricity	205,418	215,102	216,707	228,690	275,564	291,706
Heat	53,754	72,950	69,574	51,821	28,873	26,579

9.2 Energy Supply

9.2.1 Energy Distribution

Table 9-21 *Gross Final Energy*

TJ	2005	2014	2020	2030	2040	2050
Net Final Energy	**1,176,520**	**1,148,124**	**1,122,890**	**979,870**	**728,447**	**688,485**
Coal and Waste	*34,718*	*29,587*	*29,242*	*26,873*	*20,086*	*18,762*
Oil	*556,291*	*472,942*	*457,612*	*365,313*	*161,670*	*117,736*
Gas	*207,466*	*189,865*	*184,886*	*156,431*	*104,457*	*96,583*
Renewables	*118,873*	*167,678*	*164,868*	*150,742*	*137,796*	*137,119*
Electricity	*205,418*	*215,102*	*216,707*	*228,690*	*275,564*	*291,706*
Heat	*53,754*	*72,950*	*69,574*	*51,821*	*28,873*	*26,579*
Distribution losses	153,040	148,570	145,983	129,785	83,292	67,837
Coal and Waste	*61,438*	*60,287*	*59,416*	*53,403*	*35,160*	*30,716*
Oil	*31,564*	*22,935*	*22,129*	*17,270*	*6,627*	*4,429*
Gas	*19,970*	*18,416*	*17,877*	*14,756*	*8,429*	*7,094*
Renewables	*0*	*12*	*12*	*11*	*10*	*10*
Electricity	*34,814*	*40,028*	*40,019*	*39,725*	*31,263*	*24,298*
Heat	*5,253*	*6,891*	*6,530*	*4,621*	*1,804*	*1,291*
Gross Final Energy	**1,329,560**	**1,296,695**	**1,268,873**	**1,109,655**	**811,739**	**756,322**
Coal and Waste	96,156	89,874	88,658	80,275	55,246	49,478
Oil	587,855	495,877	479,741	382,583	168,297	122,165
Gas	227,436	208,282	202,764	171,187	112,887	103,677
Renewables	118,873	167,690	164,880	150,752	137,806	137,129
Electricity	240,232	255,130	256,726	268,414	306,827	316,004
Heat	59,007	79,842	76,104	56,442	30,677	27,869

9.2.2 Energy Transformation

Table 9-22 *Gross Energy Supply*

TJ	2005	2014	2020	2030	2040	2050
Untransformed Final Energy	677,653	679,012	663,398	574,329	418,654	393,827
Coal and Waste	13,087	6,377	6,263	5,477	3,418	3,016
Oil	191,816	118,135	114,142	90,100	38,565	27,882
Gas	227,436	208,282	202,764	171,187	112,887	103,677
Renewables	117,859	156,415	153,793	140,616	128,540	127,909
Biomass	*117,859*	*156,415*	*153,793*	*140,616*	*128,540*	*127,909*
Electricity	9,595	33,389	32,643	26,334	6,704	3,435
Heat	0	0	0	0	0	0
Transformed Final Energy	769,766	774,097	759,268	675,941	521,625	490,403
Coal and Waste	83,069	83,497	82,395	74,799	51,828	46,462
Oil	396,039	377,742	365,599	292,483	129,732	94,283
Gas	0	0	0	0	0	0
Renewables	1,014	11,276	11,087	10,137	9,266	9,221
Electricity	230,637	221,741	224,083	242,080	300,122	312,568
Heat	59,007	79,842	76,104	56,442	30,677	27,869
Input Transformation	886,317	858,213	839,705	741,087	553,121	515,668
Coal and Waste	172,866	149,301	146,648	129,379	77,324	65,267
Oil	418,965	387,127	373,745	298,561	131,594	95,349
Gas	114,172	61,551	59,193	45,870	18,392	13,096
Renewables	180,313	260,234	260,119	267,277	325,812	341,955
Biomass	*42,943*	*95,299*	*92,351*	*77,302*	*51,917*	*47,648*
Hydro	*132,035*	*147,608*	*148,525*	*155,033*	*166,683*	*167,436*
Wind, PV, …	*5,335*	*17,327*	*19,242*	*34,941*	*107,211*	*126,871*
Gross Energy Supply	**1,446,110**	**1,380,811**	**1,349,310**	**1,174,800**	**843,235**	**781,586**
Coal and Waste	185,954	155,678	152,912	134,856	80,742	68,283
Oil	610,781	505,262	487,886	388,661	170,159	123,232
Gas	341,608	269,832	261,957	217,057	131,279	116,772
Renewables	298,172	416,649	413,912	407,893	454,351	469,864
Biomass	*160,803*	*251,714*	*246,145*	*217,918*	*180,457*	*175,556*
Hydro	*132,035*	*147,608*	*148,525*	*155,033*	*166,683*	*167,436*
Wind, PV, …	*5,335*	*17,327*	*19,242*	*34,941*	*107,211*	*126,871*
Electricity	9,595	33,389	32,643	26,334	6,704	3,435
Heat	0	0	0	0	0	0

9.3 CO_2 Emissions

Table 9-23 CO_2 Emissions related to Functionalities

CO2 Thousand tons	2005	2014	2020	2030	2040	2050
Functionalities and related energy	**79,063**	**63,524**	**61,485**	**49,152**	**21,327**	**15,555**
Low Temperatur Heat	20,734	13,796	12,990	8,682	2,744	2,098
Coal and Waste	*447*	*187*	*178*	*133*	*75*	*69*
Oil	*7,077*	*3,591*	*3,374*	*2,216*	*600*	*415*
Gas	*4,612*	*3,873*	*3,658*	*2,517*	*962*	*791*
Renewables	0	0	0	0	0	0
Electricty	1,349	535	511	375	115	71
Heat	4,459	3,840	3,599	2,309	599	439
Distribution Losses	2,791	1,771	1,670	1,133	393	313
High Temperature Heat	18,923	16,500	16,326	15,001	10,370	9,308
Coal and Waste	*2,701*	*2,479*	*2,455*	*2,282*	*1,712*	*1,595*
Oil	*1,622*	*916*	*904*	*818*	*530*	*471*
Gas	*5,669*	*4,999*	*4,953*	*4,606*	*3,466*	*3,233*
Renewables	0	0	0	0	0	0
Electricty	2,010	1,055	1,039	900	340	213
Heat	579	695	694	682	554	514
Distribution Losses	6,342	6,356	6,280	5,715	3,767	3,282
Stationary Engines	5,886	4,059	3,996	3,500	1,669	1,290
Coal and Waste	*0*	*0*	*0*	*0*	*0*	*0*
Oil	*1,288*	*1,162*	*1,147*	*1,034*	*643*	*558*
Gas	*43*	*264*	*262*	*246*	*195*	*184*
Renewables	0	0	0	0	0	0
Electricty	3,806	2,115	2,080	1,793	667	415
Heat	0	0	0	0	0	0
Distribution Losses	749	518	507	426	165	133
Mobile Engines	31,929	28,372	27,408	21,392	6,368	2,754
Coal and Waste	*1*	*1*	*1*	*0*	*0*	*0*
Oil	*28,712*	*25,733*	*24,769*	*18,835*	*4,920*	*1,753*
Gas	*360*	*538*	*526*	*451*	*293*	*266*
Renewables	0	0	0	0	0	0
Electricty	546	233	295	613	592	436
Heat	0	0	0	0	0	0
Distribution Losses	2,311	1,868	1,818	1,493	562	299
Lighting and Electronics	1,590	797	765	577	176	105
Coal and Waste	*0*	*0*	*0*	*0*	*0*	*0*
Oil	*0*	*0*	*0*	*0*	*0*	*0*
Gas	*0*	*0*	*0*	*0*	*0*	*0*
Renewables	0	0	0	0	0	0
Electricty	1,360	672	646	491	158	97
Heat	0	0	0	0	0	0
Distribution Losses	230	125	119	85	18	8

Table 9-24 *CO_2 Emissions related to Energy Types*

CO2 Thousand tons	2005	2014	2020	2030	2040	2050
Functionalities and related energy	**79,063**	**63,524**	**61,485**	**49,152**	**21,327**	**15,555**
Coal and Waste	3,148	2,666	2,634	2,415	1,788	1,665
Oil	38,698	31,402	30,194	22,902	6,694	3,197
Gas	10,685	9,674	9,398	7,820	4,916	4,473
Renewables	0	0	0	0	0	0
Electricty	9,070	4,610	4,571	4,173	1,872	1,232
Heat	5,038	4,535	4,294	2,991	1,153	953
Distribution Losses	12,423	10,637	10,394	8,851	4,904	4,035
Losses from Distribution	**12,423**	**10,637**	**10,394**	**8,851**	**4,904**	**4,035**
Coal and Waste	5,652	5,546	5,466	4,913	3,235	2,826
Oil	2,904	2,110	2,036	1,589	610	407
Gas	1,837	1,694	1,645	1,358	775	653
Renewables	0	0	0	0	0	0
Electricty	1,537	858	844	725	212	103
Heat	492	428	403	267	72	46
CO2 Emissions from Energy Use	**79,063**	**63,524**	**61,485**	**49,152**	**21,327**	**15,555**
Coal and Waste	8,801	8,212	8,100	7,328	5,022	4,491
Oil	41,602	33,512	32,230	24,491	7,303	3,604
Gas	12,522	11,368	11,043	9,178	5,692	5,126
Renewables	0	0	0	0	0	0
Electricity	10,608	5,468	5,415	4,898	2,084	1,335
Heat	5,531	4,964	4,697	3,257	1,226	1,000

9.3 Appendix C

Appendix C.1: Basic facts about Emissions–Temperature–Uncertainty (ETU) Framework

Tab. C.1.1: Overview of IIASA's Emissions-Temperature-Uncertainty (ETU) framework

Basic feature	Description
Scientific reference	M Jonas, G Marland, V Krey, F Wagner & Z. Nahorski, 2014: Uncertainty in an emissions-constrained world. *Clim. Change*, **124**(3), 459–476, doi: 10.1007/s10584-014-1103-6.
Objective	The incentive behind developing the ETU framework was to provide an overview of how to perceive uncertainty in a systems context that seeks to constrain global warming. The framework allows understanding uncertainty across temporal scales and on reconciling short-term GHG emission commitments with long-term efforts to meet global temperature targets in 2050 and beyond.
Diagnostic uncertainty and risk	Diagnostic uncertainty is the uncertainty contained in inventoried emission estimates and relates to the risk that true GHG emissions are greater than inventoried emission estimates reported in a specified year.
Prognostic uncertainty and risk	Prognostic uncertainty refers to cumulative emissions between a start year and a future target year and relates to the risk that an agreed temperature target is exceeded.
Scientific pillar	The ETU framework builds on the contraction and convergence (C&C) approach (GCI 2012) resulting from cumulative emissions that are constrained. The ETU framework expands this approach by taking diagnostic and prognostic uncertainty on board. The strength of the cumulative-emissions based C&C approach is that it can be used to shortcut the serial logic 'GHG emissions → GHG concentrations → global temperature increase'. Cumulative emissions (here as of 2000 until 2050) have been shown to be a good predictor for the expected temperature rise in the future (here in 2050 and beyond).
Assumptions I	Emission targets derived for 2050 are exclusively available for technospheric emissions. The imperative for net emissions from LU activities is that these will be reduced linearly to zero by 2050. It is presupposed that deforestation and other LU mismanagement will cease and that net emissions balance.
Assumptions II	The hidden assumptions are that (i) the remainder of the biosphere (including oceans) stays in or returns to an emissions balance; (ii) this return, which refers to CO_2-C, implies in turn that emissions and removals of CH_4, N_2O, etc. also return to an emissions

	balance; and (iii) these returns happen without systemic surprises of the terrestrial biosphere.
Assumptions III	Additional assumptions exist when making the step from a 2 °C global warming target to global warming targets of 3 and 4 °C; namely that (i) the risk of overshooting is comparatively stable and independent of the particular warming situation, equilibrium or transient, when going from, e.g., 2 to 3 °C; and (ii) deviations from this assumption are minor compared to the considerable change in risk when going from, e.g., 2 to 3 °C under either warming, equilibrium or transient.
Data availability	Web-based knowledge platform developed as a part of ClimTrans2050 project and on IIASA web-page
Thematic scope	GHG emissions: CO_2 and CO_2-eq (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 combined)
Thematic resolution	technosphere, land use / land-use change, and trade (embodied emissions)
Diagnostic period	1990–2012/13
Monitoring periods (to monitor both reported data and scenarios vis-à-vis linear GHG emission target paths)	1990–2050, 2000-2050 and 2010-2050
Period for comparative, long-term global warming scenarios	2000–2100
2050 temperature (global warming) targets	2, 3 and 4 °C
GHG emissions over time (standard)	Without and with uncertainty by country: National linear target paths for emissions, which are consistently embedded globally, - for two temporal (predictor) regimes: 1990–2050 and 2000–2050; - for CO2 and all six Kyoto GHGs (cumulative); - for individual spheres: technosphere and land use / land-use change; - for three global warming targets: 2, 3 and 4 °C; and - which allow monitoring Austria's performance—past (with and without embodied emissions) as well as projected achievements—

	in complying with these warming targets.
Units	emissions, emissions per capita, emissions per GDP (the ETU framework allows translating between these units)
Consistency	National linear target paths for emissions are consistently embedded in the global context (summing over all countries' national target paths yields the global emissions target path).
Monitoring	National linear target paths for emissions serving as reference in monitoring the performance of countries—past as well as prospective achievements—in complying with a future warming target in a quantified uncertainty-risk context.

Appendix C.2: Global emissions reductions targets

Tab. C.2.1: 2050 global emissions targets for linear reductions starting in 1990, 2000 and 2010 are given together with indication of the most likely level of global warming they would achieve.

Period	Budget of global cumulative GHG emissions for period	2050 global emission targets		Compliance with temperature targets in 2050 (risk of exceedance < 50%)			
	Gt CO_2-eq	Gt CO_2-eq	t CO_2-eq/cap	2 °C	3 °C	3 – 4 °C	≥ 4 °C
1990–2050	1890	25.5	2.6	X			
	2190	35.5	3.6		X		
	2490	45.5	4.7			X	
	2790	55.5	5.7				X
2000–2050	1500	20.8	2.1	X			
	1800	32.8	3.4		X		
	2100	44.8	4.6			X	
	2400	56.8	5.8				X
2010–2050	1070	5.5	0.6	X			
	1370	20.5	2.1		X		
	1670	35.5	3.6			X	
	1970	50.5	5.2				X

Figures C.2.1 – C.2.4 show the historical global GHG emissions from technosphere (thick black line) and land – use sector (thick brown line). While land – use related emissions seem to follow the linear reduction path towards sustainable land – use (grey dashed line) required by the ETU framework, the technospheric emissions – both total and per capita – are rising sharply since the beginning of the 21st century. Two decades of delays in undertaking a serious mitigation efforts result in reductions targets becoming more and more challenging to meet, which is clearly visible in increasing slopes of linear reductions target paths obtained via the ETU framework (yellow, orange and red lines). The paths of reductions starting in 2010 are considerably steeper than the others due to fast depletion of 2000 – 2050 emissions budgets over the last decade.

The linear reduction target paths are compared against emissions projections generated by the GTEM, IMAGE and POLES models for ambitious reductions scenarios (dark, medium and light green dashed lines, respectively). Using linear target paths as a reference one can clearly see that all three scenarios lead to warming between 2°C and 3°C.

We plot also projections of CO_2-emissions related to energy production, published by the International Energy Agency (IEA) for the three representative scenarios corresponding to 2°C, 4°C and 6°C warming levels (light, medium and dark olive dotted lines, respectively). Comparison of these projections with linear target paths we conclude that IEA's 4°C and 6°C scenarios agree with findings of the ETU framework, but most stringent 2°C scenario is rather more likely to lead to the 3°C warming instead. For further details on method and scenarios see IIASA Interim Report IR-16-003 "Uncertainty in an Emissions Constrained World: Method Overview and Data" (http://climtrans2050.wifo.ac.at/tiki-index.php?page=Project+Output).

Fig. C.2.1a: Historical global technospheric and land-use related GHG emissions, linear reduction target paths likely to secure 2°C warming target and future emissions scenarios generated by models external to ETU framework.

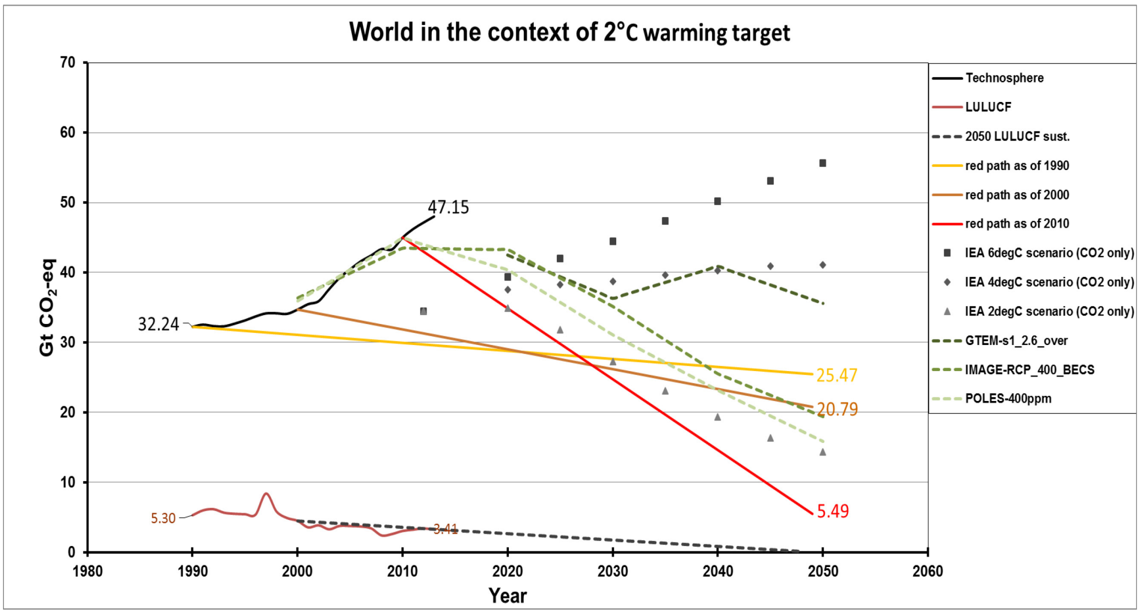


Fig. C.2.1b: Historical global per capita emissions form technospheric and land-use sector, linear reduction target paths likely to secure 2°C warming target and future emissions scenarios generated by models external to ETU framework.

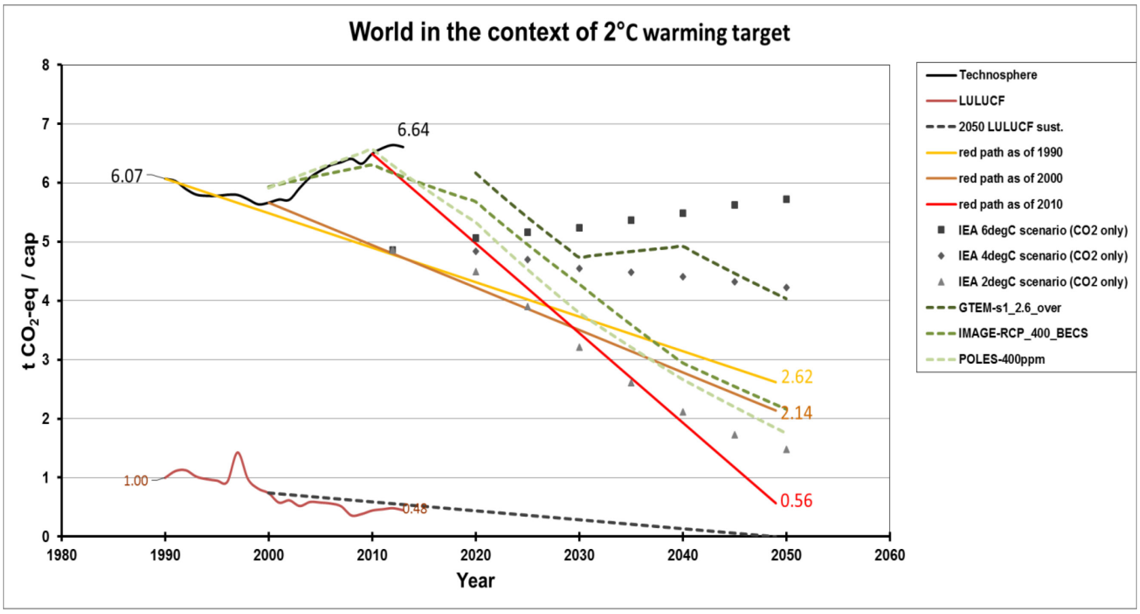


Fig. C.2.2a: Historical global technospheric and land-use related GHG emissions, linear reduction target paths likely to secure 3°C warming target and future emissions scenarios generated by models external to ETU framework.

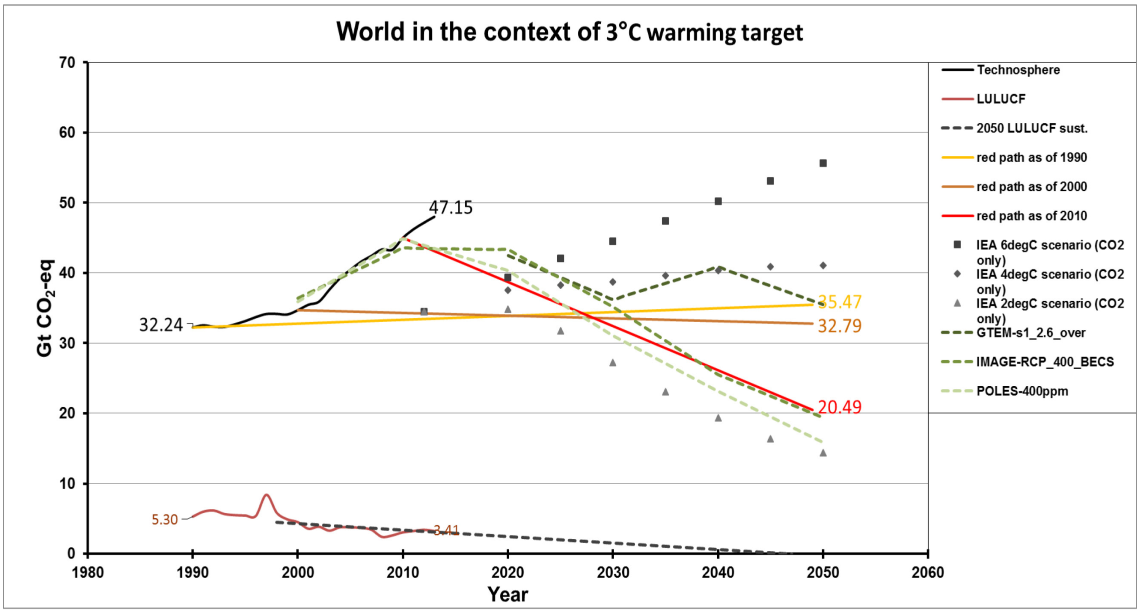


Fig. C.2.2b: Historical global per capita emissions form technospheric and land-use sector, linear reduction target paths likely to secure 3°C warming target and future emissions scenarios generated by models external to ETU framework.

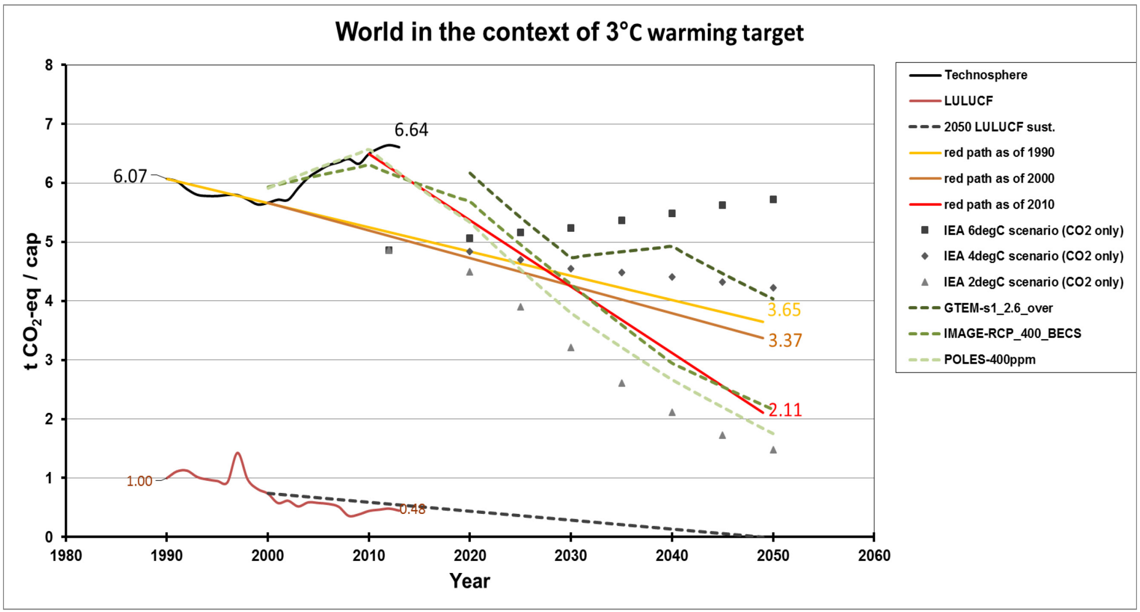


Fig. C.2.3a: Historical global technospheric and land-use related GHG emissions, linear reduction target paths likely to secure secure warming target between 3°C and 4°C, and future emissions scenarios generated by models external to ETU framework.

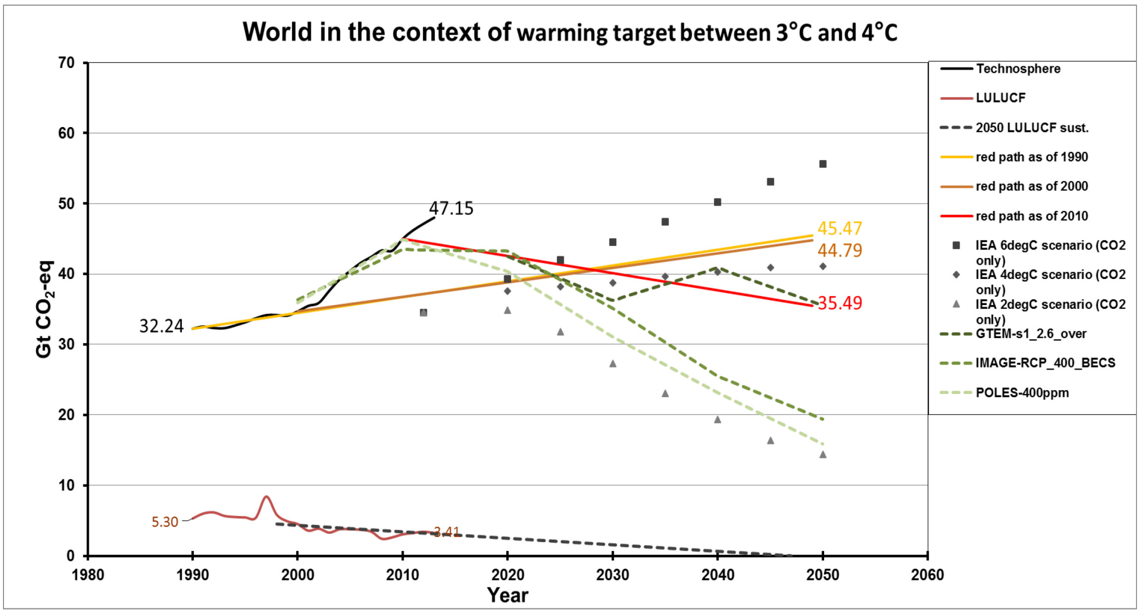


Fig. C.2.3b: Historical global per capita emissions form technospheric and land-use sector, linear reduction target paths likely to secure warming target between 3°C and 4°C, and future emissions scenarios generated by models external to ETU framework.

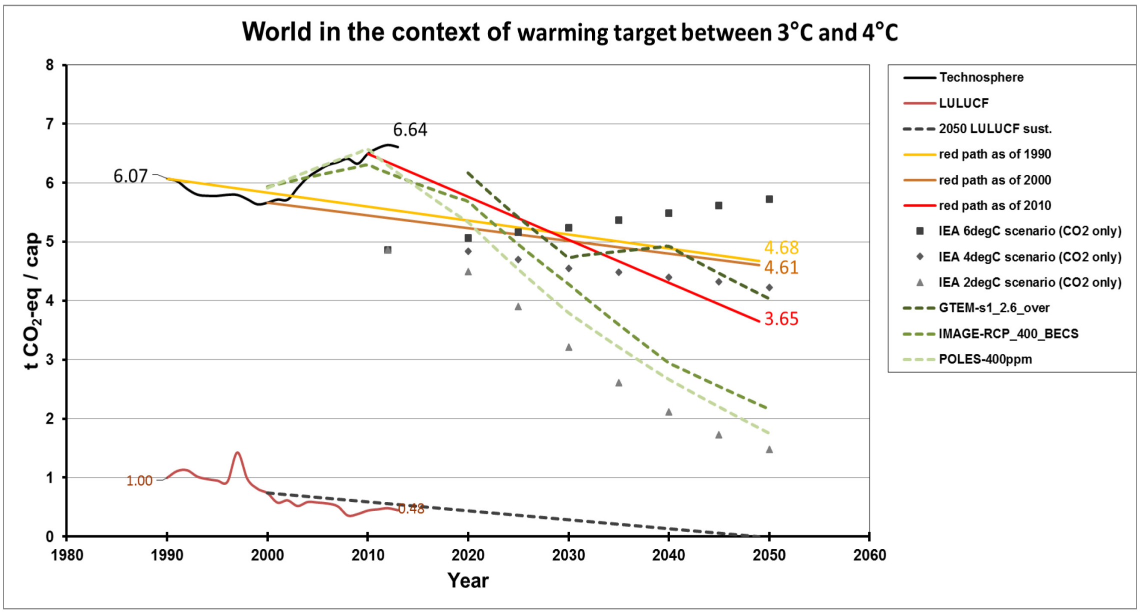


Fig. C.2.4a: Historical global technospheric and land-use related GHG emissions, linear reduction target paths likely to secure 4°C warming target and future emissions scenarios generated by models external to ETU framework.

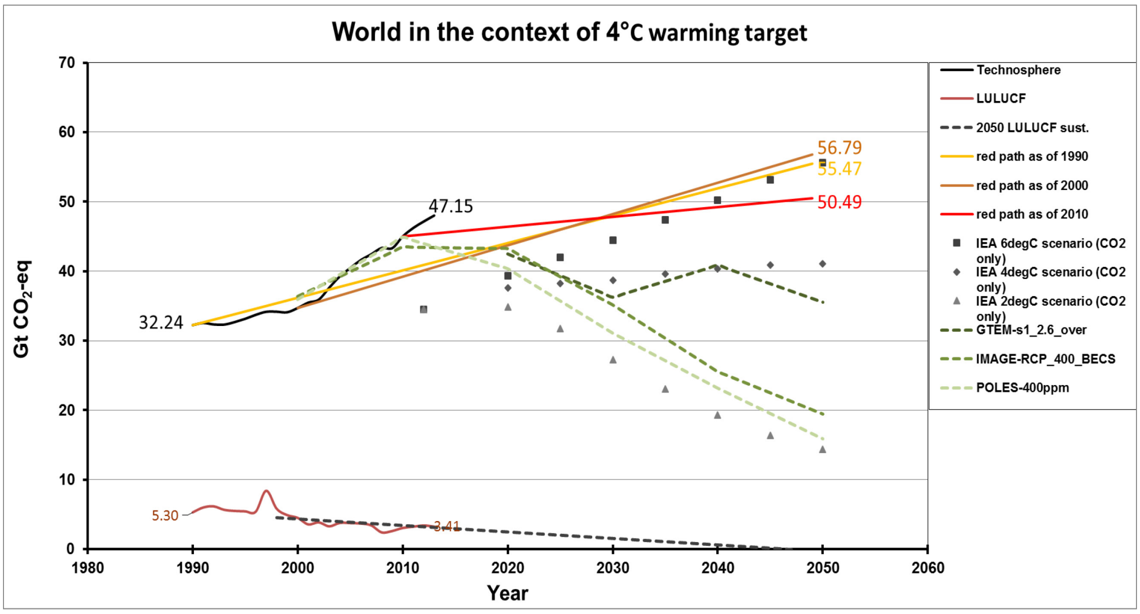
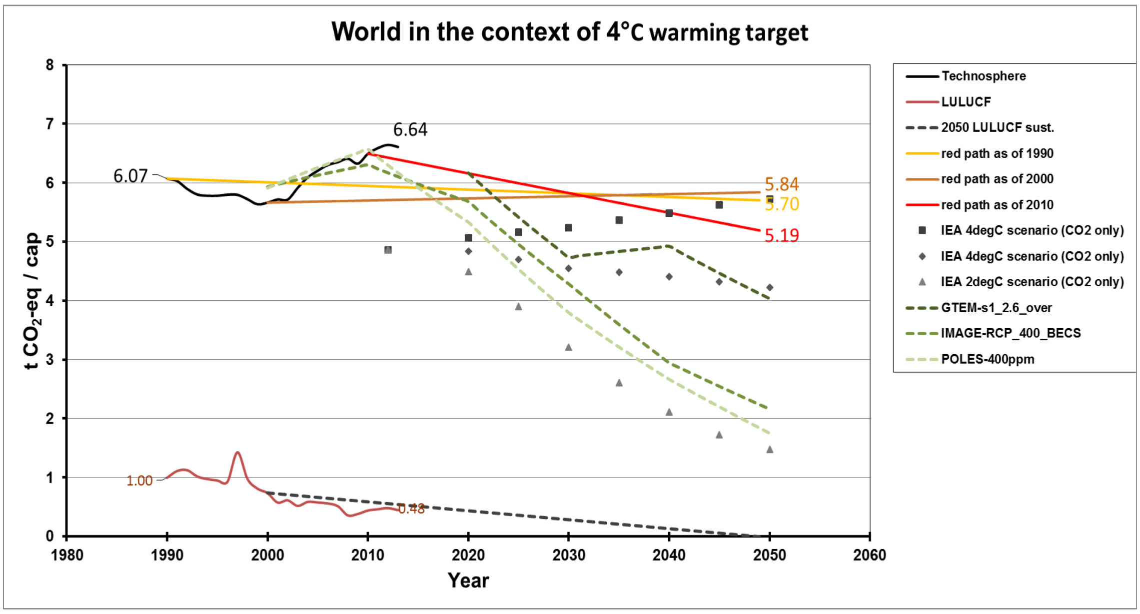


Fig. C.2.4b: Historical global per capita emissions form technospheric and land-use sector, linear reduction target paths likely to secure 4°C warming target and future emissions scenarios generated by models external to ETU framework.



Appendix C.3: Austria's emissions reductions targets and assessment of future emissions scenarios

Table C.3.1 summarises Austria's per capita emissions cuts required to achieve global per capita emissions targets (GEE targets) obtained via the ETU framework (cf. Appendix C.2). These targets were calculated for the mitigation efforts starting in 1990, 2000 and 2010. The reduction requirements are specified for technospheric and land – use sectors and were calculated with respect to the start year emissions without the international trade taken into account.

Tab. C.3.1: Per capita emissions of Austria in years 1990, 2000 and 2010 and emission reductions needed to meet GEE targets in 2050.

Sector	1990 Per-capita emissions w/o trade	1990 Per-capita emissions with trade	2050 Global emissions equity targets [in t CO_2-eq/cap]			
			2.6	3.6	4.7	5.7
			1990–2050 emission reduction w/o trade			
	t CO_2-eq/cap	t CO_2-eq/cap	% / cap	% / cap	% / cap	% / cap
Technosphere	10.17	13.48	74	64	54	44
LUC	-1.29	unknown	100% (Imperative: Net emissions from LUC reduce linearly to zero until 2050!)			
Sector	2000 Per-capita emissions w/o trade	2000 Per-capita emissions with trade	2050 Global emissions equity target [in t CO_2-eq/cap]			
			2.1	3.4	4.6	5.8
			2000–2050 emission reduction w/o trade			
	t CO_2-eq/cap	t CO_2-eq/cap	% / cap	% / cap	% / cap	% / cap
Technosphere	10.02	13.48	79	66	54	42
LUC	-1.90	-1.84	100% (Imperative: Net emissions from LUC reduce linearly to zero until 2050!)			
Sector	2010 Per-capita emissions w/o trade	2010 Per-capita emissions with trade	2050 Global emissions equity target [in t CO_2-eq/cap]			
			0.6	2.1	3.6	5.2
			2010–2050 emission reduction w/o trade			
	t CO_2-eq/cap	t CO_2-eq/cap	% / cap	% / cap	% / cap	% / cap
Technosphere	10.11	13.31	94	79	64	49
LUC	-0.46	unknown	100% (Imperative: Net emissions from LUC reduce linearly to zero until 2050!)			

Figures C.3.1a – C.3.4a present technospheric part of Austria's emissions. The thick black line represents the GHG emissions from technosphere that occurred on the territory of Austria only, while the thin black line represents all the Austria's technospere emissions with the international trade taken into account (i.e., emissions occurred outside Austrian territory that resulted from the production and transport of goods consumed in Austria). Austria's technospheric emissions exhibit decreasing trend over the last decade with relatively stable share of emissions embodied in international trade.

Austria (and virtually all western developed countries) is facing daunting 90% - 95% emissions reductions with respect to current level, if she wants to be on track towards the 2°C warming target (cf. Tab. B.3.1). These targets cannot be achieved only by a technological tweaks and increase of energy efficiency. This can be clearly seen when comparing linear emissions target paths with Austria's projections of future GHG emissions assuming implementation of already existing mitigation measures (WEM scenario – light olive symbols) and additional, currently planned measures (WAM scenario – dark olive symbols). The WEM scenario considers the policies and measures (PAMs) implemented before 1st of May 2014. The effects of these policies and measures were assessed jointly, with their interactions taken into account. Investigated PAMs were selected on the basis of their relevance for reductions of emissions from at least one of emissions sectors as defined in the UNFCCC guidelines. The WAM scenario takes into account also planned polices and measures which have a chance to be adopted and implemented in time to influence the emissions in the period between 2015 and 2035. Comparing these emissions projections against the ETU target paths one concludes that even more ambitious WAM scenario is hardly sufficient to generate reductions corresponding to the 4°C warming target. The detailed list of considered policies and measures and exact definitions of WEM and WAM scenarios are given in chapters 4 and 5 of the report (UBA, 2015).

The thick black dotted lines on Figures C.3.1a – C.3.4a represent CO_2 emissions (in this case practically equal to all GHG emissions) attributed to all energy related functionalities (i.e., Low Temperature Heat, High Temperature Heat, Stationary Engines, Mobile Engines and Lighting and Electronics). The thick light and dark green dotted lines represent projections of CO_2 emissions corresponding to the two following scenarios:

- Moderately Ambitious (MA) scenario which will bring down CO_2 emissions to 42% compared to 2005 level. It is rather generous in the expansion of functionalities and is mainly based on increases of productivity and changes in the energy mix which can already be observed.
- Highly Ambitious (HA) scenario which will require disruptive changes, in particular in mobility, leaving only 15% of transport based on combustion engines and a thorough improvement in the energetic efficiency of the building stock. Also some functionalities may be considered redundant and are therefore slightly reduced.

For further details on energy related functionalities and scenarios of their further development see chapter 4.1.

With use of the ETU framework we may assess the compatibility of these scenarios with global warming targets of 2°C, 3°C, 3°C - 4°C and 4°C or higher. This we do in the three following steps:

- We specify the share historical GHG emissions ascribed to the considered functionalities.

- We assume scenarios of further evolution of these functionalities and calculate future emissions resulting from these scenarios.
- We compare the cumulative emissions until 2050 resulting from considered scenarios against constrains for Austria's cumulative GHG emissions until 2050 corresponding to abovementioned warming targets.

Tables C.3.2 – C.3.5 contain results of step 3. Red entries in the tables mark exceeding of the total Austria's cumulative GHG emissions budget corresponding to a given warming target. On top of the emissions resulting from the considered scenario one should leave the margin for emissions from other functionalities. Thus we conclude that the MA scenario is in line with a warming target below 4°C and the HA scenario corresponds to target of 3°C.

Tab. C.3.2: Austria's energy related functionalities in context of 2°C warming target.

Period	Austria's all GHG emissions budget	Cumulative CO2 emissions for MA scenario	Cumulative CO2 emissions for HA scenario
1990 - 2050	3115 Mt CO_2-eq	3653 Mt CO_2	3362 Mt CO_2
2000 - 2050	2532 Mt CO_2-eq	2988 Mt CO_2	2696 Mt CO_2
2010 - 2050	1807 Mt CO_2-eq	2210 Mt CO_2	1919 Mt CO_2

Tab. C.3.3: Austria's energy related functionalities in context of 3°C warming target.

Period	Austria's all GHG emissions budget	Cumulative CO2 emissions for MA scenario	Cumulative CO2 emissions for HA scenario
1990 - 2050	3418 Mt CO_2-eq	3653 Mt CO_2	3362 Mt CO_2
2000 - 2050	2836 Mt CO_2-eq	2988 Mt CO_2	2696 Mt CO_2
2010 - 2050	2111 Mt CO_2-eq	2210 Mt CO_2	1919 Mt CO_2

Tab. C.3.4: Austria's energy related functionalities in context of warming target between 3°C and 4°C.

Period	Austria's all GHG emissions budget	Cumulative CO2 emissions for MA scenario	Cumulative CO2 emissions for HA scenario
1990 - 2050	3722 Mt CO_2-eq	3653 Mt CO_2	3362 Mt CO_2
2000 - 2050	3139 Mt CO_2-eq	2988 Mt CO_2	2696 Mt CO_2
2010 - 2050	2414 Mt CO_2-eq	2210 Mt CO_2	1919 Mt CO_2

Tab. C.3.5: Austria's energy related functionalities in context of 4°C warming target.

Period	Cumulative CO2 emissions for MA scenario	Cumulative CO2 emissions for MA scenario2	Cumulative CO2 emissions for HA scenario
1990 - 2050	4025 Mt CO_2-eq	3653 Mt CO_2	3362 Mt CO_2
2000 - 2050	3442 Mt CO_2-eq	2988 Mt CO_2	2696 Mt CO_2
2010 - 2050	2717 Mt CO_2-eq	2210 Mt CO_2	1919 Mt CO_2

Dark blue and graphite dashed lines on Figures C.3.1a – C.3.4a denote emissions reductions targets for which Austria agreed in Kyoto protocol (7% reduction of GHG emissions with respect to 1990 level) and in Burden Sharing mechanism (13% reduction w.r.t. 1990 emissions), respectively. Austria's targets within Effort Sharing mechanism (16% w.r.t. 2005 emissions) implementing the EU's Climate and Energy Package are marked with light blue dashed line. All these short term mitigation efforts follows linear reduction paths leading to a level of warming around 4°C.

Figures C.3.1b – C.3.4b present the view of Austria's technospheric emissions and reduction targets in per capita terms. They also show the historical per capita emissions from land – use sector, both with and without international trade taken into account (dotted and solid brown lines, respectively). Austria's territory has been a sink over the last two decades (1990 – 2010). Evidently, international trade has minimal effect on that picture. As the ETU framework requires the land – use related emissions to converge to zero by 2050, Austria, being a sink, is on the safe side of that requirement. However the strength of Austria's sink has decreased over the last decade and is approaching zero emissions much faster than the target path for land – use emissions assumed by the ETU framework (dark grey dashed line).

In summary, meeting GHG emissions reduction requirements corresponding to the 2°C global warming target will be an immense challenge for Austria since none of analysed policies or scenarios comply with this target. Instead, simply maintaining the reduction rates assigned to Austria by Burden Sharing or Effort Sharing mechanisms beyond the commitment periods, or relying on currently planned or implemented mitigation measures would put Austria on track towards the reality of future global warming of 4°C. A much more vigorous climate action is required to avoid such (likely to be catastrophic) outcome.

Fig. C.3.1a: Analysis of technosphere emissions of Austria: historical GHG emissions, linear reduction target paths complying with 2°C warming target, intended reductions for mitigation efforts and projections of future emissions.

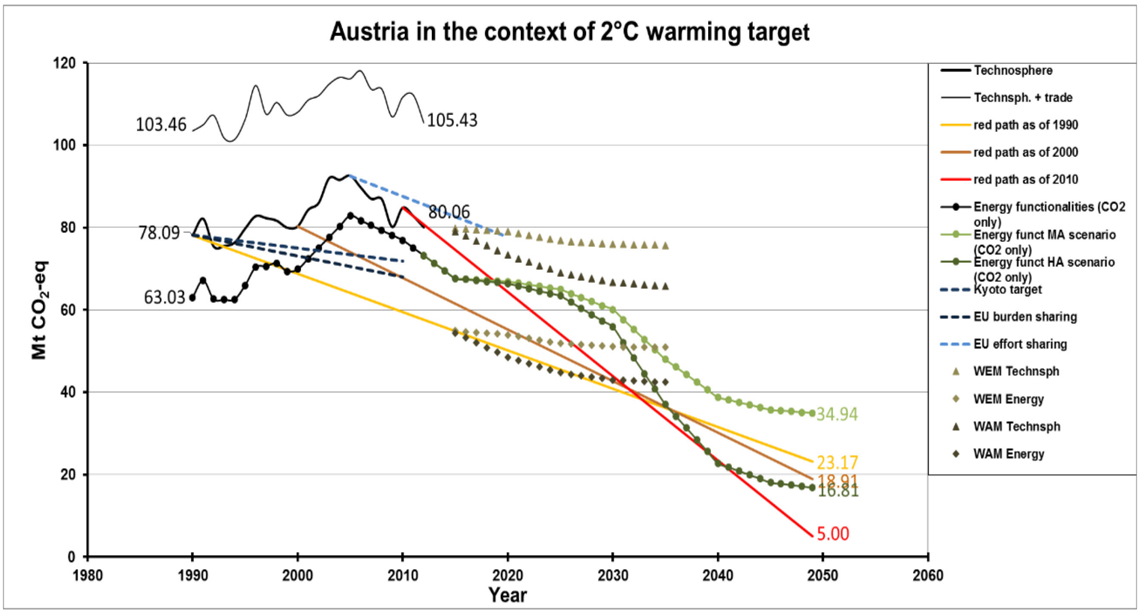


Fig. C.3.1b: Historical per capita GHG emissions of Austria form technospheric and land-use sector, linear reduction target paths complying with 2°C warming target, intended reductions for mitigation efforts and projections of future emissions.

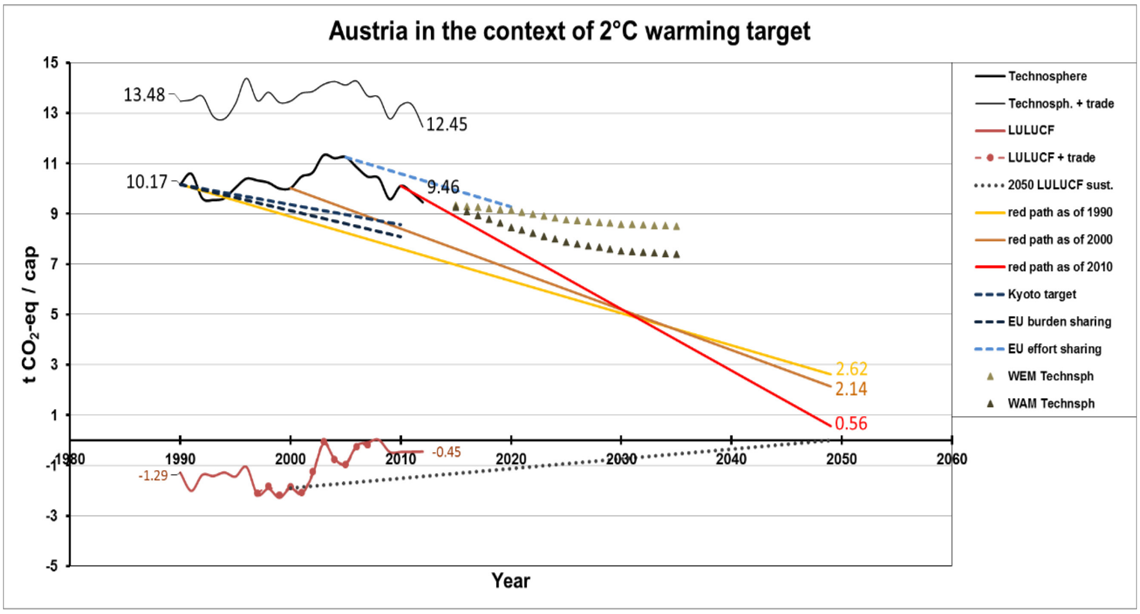


Fig. C.3.2a: Analysis of technosphere emissions of Austria: historical GHG emissions, linear reduction target paths complying with 3°C warming target, intended reductions for mitigation efforts and projections of future emissions.

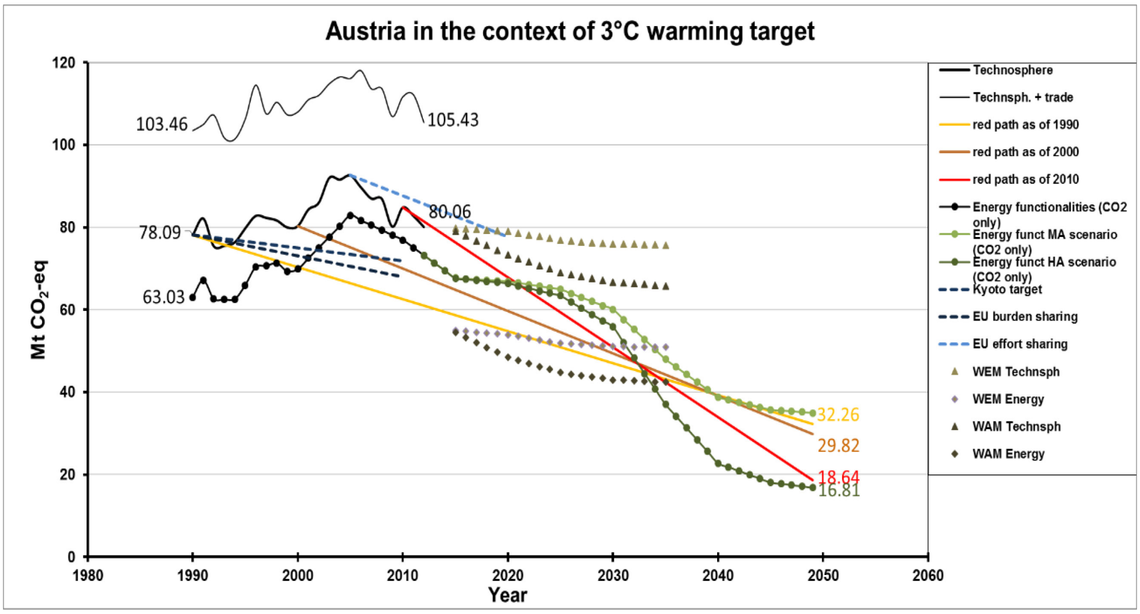


Fig. C.3.2b: Historical per capita GHG emissions of Austria form technospheric and land use sector, linear reduction target paths complying with 3°C warming target, intended reductions for mitigation efforts and projections of future emissions.

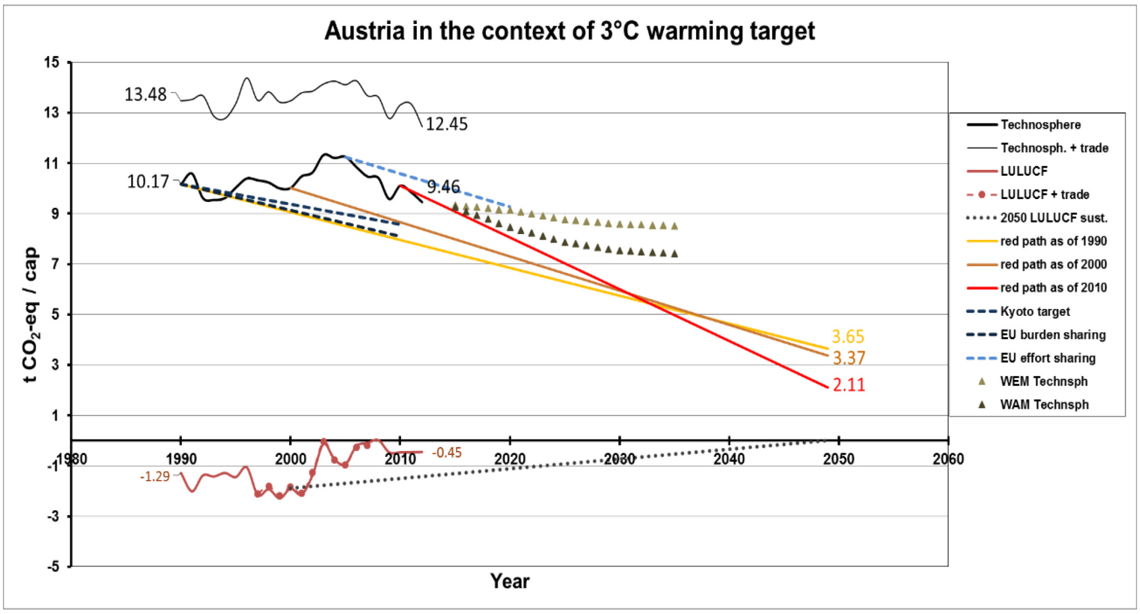


Fig. C.3.3a: Analysis of technosphere emissions of Austria: historical GHG emissions, linear reduction target paths complying with warming target between 3°C and 4°C, intended reductions for mitigation efforts and projections of future emissions.

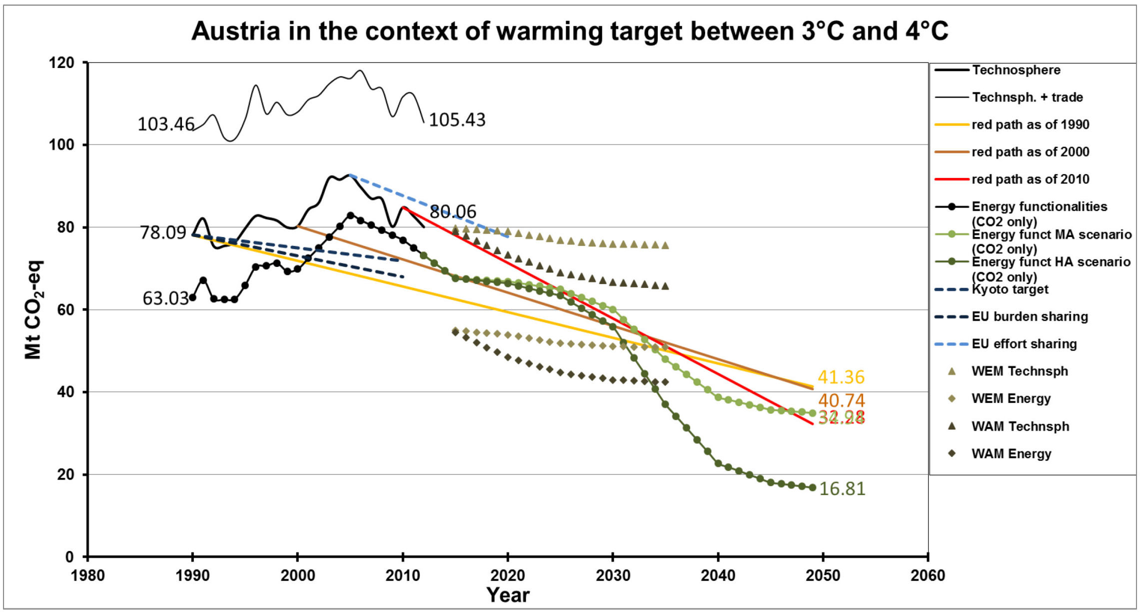


Fig. C.3.3b: Historical per capita GHG emissions of Austria form technospheric and and-use sector, linear reduction target paths complying with warming target between 3°C and 4°C, intended reductions for mitigation efforts and projections of future emissions.

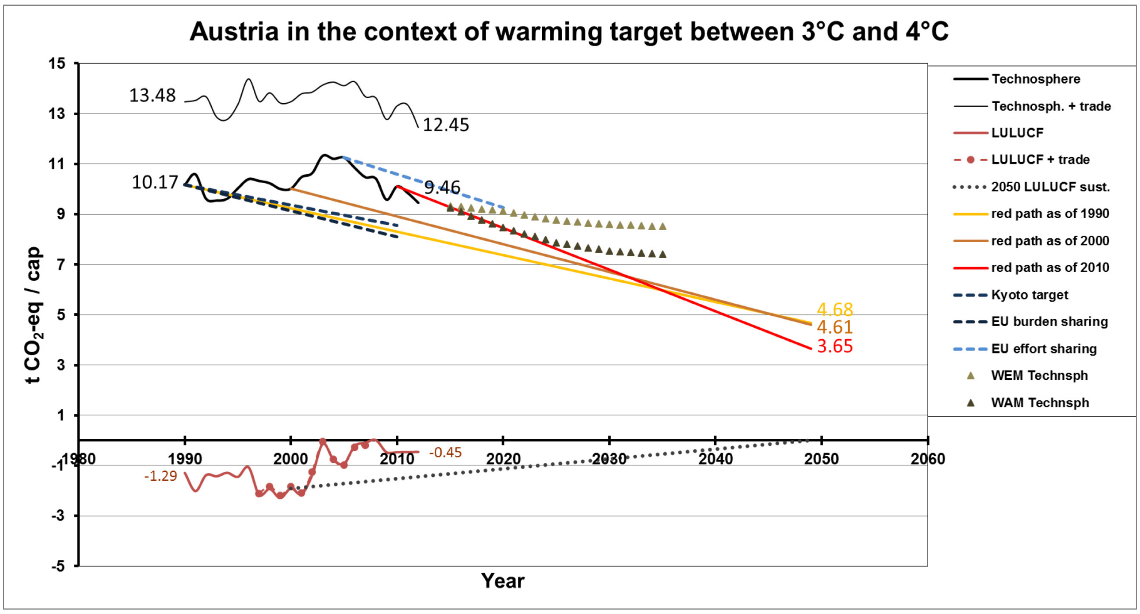


Fig. C.3.4a: Analysis of technosphere emissions of Austria: historical GHG emissions, linear reduction target paths complying with 4°C warming target, intended reductions for mitigation efforts and projections of future emissions.

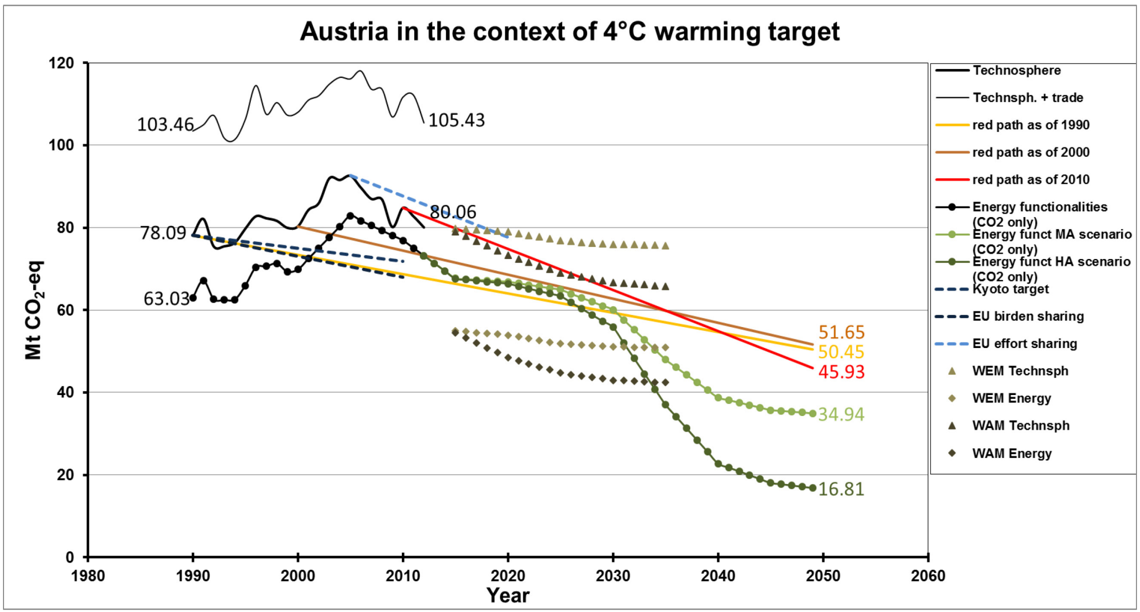


Fig. C.3.4b: Historical per capita GHG emissions of Austria form technospheric and land use sector, linear reduction target paths complying with 4°C warming target, intended reductions for mitigation efforts and projections of future emissions.