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Endbericht

STOEMSys – Towards a Sustainability Transition Open Economic Modelling System

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Contents

Vorbemerkung **6**

1 Executive Summary **8**

I STOEMSys – Towards a Sustainability Transition Open Economic Modelling System **11**

2 Introduction **12**
- 2.1 Investment Oriented Climate Policy for a Sustainability Transition 12
- 2.2 Analysing a Green Investment Impulse 13
- 2.3 From the "German Green-Growth Module" to the Sustainability Transition Open Economic Modelling System (STOEMSys) 14
- 2.4 The Structure of This Report 15

3 Cost-Benefit Analysis of Investment-Oriented Climate Policies **17**
- 3.1 A Simple STOEMSys Model 17
- 3.2 A Preliminary STOEMSys Model With Price Dynamics 19
- 3.3 An Enhanced CGE Model 20
- 3.4 A Version of IMACLIM-WEM 21

4 Challenges **23**
- 4.1 Multiple Equilibria and Non-Equilibrium Dynamics 23
- 4.2 A Complementarity Problem: Understanding the Principles Versus Simulating Real-World Economies 25
- 4.3 Transparency of Economic Modelling 26

5 What STOEMSys Is **27**

6 STOEMSys Economic Components **30**
- 6.1 Mechanisms for a Sustainability Transition 30
- 6.2 Climate-Economic Perspective 32
- 6.3 Metrics for Costs and Benefits 33
- 6.4 Agent-based Design 33

7 STOEMSys Computational Components **38**
- 7.1 Open Source Code 38
- 7.2 System Language 39
- 7.3 Economic Types Library 39
- 7.4 Extended MASON Framework (EMF) 41
- 7.5 Post-processing and Visualization 43
- 7.6 Rapid Prototyping Framework 44

7.7 Virtual Machine 45

8 STOEMSys Implementation Components 46
8.1 Modular Architecture 46
8.2 Aggregate Agents 46
8.3 Price Dynamics Through Expectations and Learning 48
8.4 Modules 50
8.5 Sectoral Module Interface 57
8.6 Data- and Configuration Files 61
8.7 Documentation 62

9 Current State of the Analysis and Further Development 63
9.1 Simulations of a Green Investment Impulse in the Buildings Sector 63
9.2 Money Supply and Inflation 67
9.3 Further Development 72

10 Documentation of a Macro-Module Coupled with Buildings Sector 76
10.1 Overview 76
10.2 Design Concepts 80
10.3 Functional Specification 82

11 Data and Calibration 94
11.1 Calibration of Macro-Module S 94
11.2 The Default Data File for Macro-Module S with Simple Buildings Module 97

II Supplementary Project Work 101

12 Stakeholder Dialogues 102
12.1 Workshops 102
12.2 Conferences 104
12.3 Bilateral Meetings 106

13 Sector Analysis: Investment needs and economic impact 107
13.1 General Findings 107
13.2 Energy Sector 108
13.3 Households 109
13.4 Transportation 110
13.5 Industry 111
13.6 Summary 111

14 Documentation of sectoral models 113
14.1 Introduction 113
14.2 Energy models 113
14.3 ISI Industry model 116
14.4 IKARUS model 116

14.5 ASTRA model 119
14.6 TREMOD model 120
14.7 CAPRI model 121
14.8 PANTA RHEI 121

15 Conclusion **124**

Schlussbemerkung **126**

A Stakeholder Dialogues: Workshop- and Conference-Programmes, Presentations by GCF Staff **135**

B GHG Emission Reduction Scenarios **136**

List of Figures

Fig. 1: STOEMSys . . . 9
Fig. 2: GDP . . . 18
Fig. 3: Emissions . . . 18
Fig. 4: GDP . . . 19
Fig. 5: Emissions . . . 20
Fig. 6: GDP and Employment . . . 21
Fig. 7: GDP growth . . . 21
Fig. 8: STOEMSys . . . 28
Fig. 9: MASON display screenshot . . . 42
Fig. 10: GGobi screenshot showing the brushing feature . . . 44
Fig. 11: Rapid Prototyping Framework example . . . 45
Fig. 12: Modular Architecture . . . 47
Fig. 13: Price Adjustment by Learning . . . 49
Fig. 14: Price Dynamics on the Goods Market . . . 50
Fig. 15: Overview of MM-A . . . 51
Fig. 16: UML diagram showing the main structure . . . 58
Fig. 17: GDP . . . 64
Fig. 18: GDP growth . . . 65
Fig. 19: Buildings emissions . . . 65
Fig. 20: Emissions . . . 66
Fig. 21: Supplied vs. sold quantities . . . 66
Fig. 22: Price of generic good . . . 67
Fig. 23: Constant Amount of Money . . . 68
Fig. 24: Growth Rates to Figure 23 . . . 69
Fig. 25: Increase on Household's Side . . . 69
Fig. 26: Central Bank Finances Net Investments . . . 71
Fig. 27: Growth Rates to Figure 26 . . . 71
Fig. 28: Money Supply with Inflation Target . . . 72
Fig. 29: Growth Rates to Figure 28 . . . 72
Fig. 30: GDP with oscillations . . . 73
Fig. 31: STOEMSys MMS & BM . . . 77
Fig. 32: Modular Architecture . . . 78
Fig. 33: Calibration results . . . 96
Fig. 34: GHG Emissions for EU28 in Mt CO2 equivalent . . . 108
Fig. 35: GHG Emissions by sector for 1990, 2011 and estimated for 2030 . . . 112
Fig. 36: CO_2 effect . . . 114
Fig. 37: PowerACE model . . . 115
Fig. 38: ISIndustry model . . . 117
Fig. 39: Structure of the MIS model . . . 118
Fig. 40: Module structure of the ASTRA model . . . 120

Fig. 41: Model Structure of PANTA RHEI 122

List of Tables

Table 1: MM-A Variables 52
Table 2: Agents 63
Table 3: Scenarios 64
Table 4: Dependences of MM-A State Variables 74
Table 5: Dahlem guidelines summary template 76
Table 6: State and auxiliary variables of firm and household or of their interaction . . 83
Table 7: Market Overview 88
Table 8: Calibration Variables, Values and Functions 94
Table 9: Default data 99

List of Boxes

Box 1: Firm’s Decision Functions 54

Vorbemerkung

Der vorliegende Bericht stellt die Ergebnisse des Projekts Bewertungsmodul Klimapolitik (Förderkennzeichen 03KSE041, Mai 2012 – Dezember 2014) dar. Er ist sowohl im Anschluss an die vorherigen Projektberichte (Jaeger et al. 2012a; Jaeger et al. 2013; Jaeger et al. 2014), als auch als Zusammenfassung wichtiger Aspekte dieser zu verstehen.

Der Bericht gliedert sich in zwei Teile. Teil I stellt das entwickelte offene ökonomische Modelliersystem für eine Nachhaltigkeitswende (STOEMSys – Sustainability Transition Open Economic Modelling System) vor und ist in folgende Kapitel eingeteilt:

Kapitel 1 fasst die wichtigsten Punkte zusammen.

Kapitel 2 stellt kurz die praktische Herausforderung für Klimapolitik und die wissenschaftliche Herausforderung, erstere zu analysieren, dar. Außerdem wird ein Überblick über die Struktur des Berichts gegeben.

Kapitel 3 entwirft die Forschungsrichtung für die Kosten-Nutzen-Analyse investitionsorientier Klimapolitik mithilfe (teils vorläufiger) Ergebnisse aus verschiedenen, aber zusammenhängenden Forschungsarbeiten des Global Climate Forum.

Kapitel 4 fasst die wichtigsten Herausforderungen für die Identifizierung von “Win-win"–Strategien für Klima und Wirtschaft in der Kosten-Nutzen-Analyse zusammen. Auch diese sind ein Ergebnis aus der Arbeit des Projekts, insofern, als einige Herausforderungen sich erst durch diese Arbeit herausgestellt haben.

Kapitel 5 stellt das Sustainability Transition Open Economic Modelling System (STOEMSys), das zentrale Projektergebnis, kurz dar.

Kapitel 6 beschreibt ökonomische Komponenten von STOEMSys.

Kapitel 7 beschreibt rechentechnische Komponenten von STOEMSys.

Kapitel 8 beschreibt Implementierungskomponenten von STOEMSys.

Kapitel 9 stellt den aktuellen Stand von Analysen mit STOEMSys vor und weist auf Fragestellungen für weitergehende Forschung hin.

Kapitel 10 dokumentiert das Nachfolgemodell des Prototypen und der Interimsversion aus den vorherigen Projektberichten: das Modell besteht aus einem STOEMSys Makromodul kombiniert mit einem Gebäudemodul.

Kapitel 11 beschreibt die Kalibrierung dieses Modells und dokumentiert das zugehörige Datenfile.

Teil II fasst in 3 Kapiteln ergänzende Projektarbeiten zusammen.

Kapitel 12 berichtet über Workshops, Konferenzen und bilaterale Treffen, die im Laufe des Projekts im Arbeitspaket “Expertendialog" stattgefunden haben.

Kapitel 13 fasst sektorale Analysen zusammen, die Grundlage für die Modul- und Szenarienentwicklung waren.

Kapitel 14 liefert eine Zusammenfassung einer Dokumentation von sektoralen Modellen, die als Hintergrundinformation für die Modulentwicklung in STOEMSys erstellt wurde.

Der Bericht stellt somit folgende Meilensteine verschiedener Arbeitspakete des Projekts zusammen:

- AP2 Expertendialog: MS Workshop (Kapitel 12.1.3) und MS Konferenz (Kapitel 12.2.2)
- AP4 Modulentwicklung: MS Endversion (Kapitel 8.4) und MS Dokumentation Endversion (Kapitel 10)
- AP5 Datenfiles und Szenarienentwicklung: MS Schnittstellen und Datenfile mit Dokumentation (Kapitel 8.5 und 11.2.2) und MS Exemplarische Szenarien (Kapitel 3)

Wie alle vorhergehenden Berichte ist auch dieser Bericht in englischer Sprache verfasst, weil dies die gängige Wissenschaftssprache auf dem zu untersuchenden Gebiet ist. Somit werden eine weitere Verbreitung der Inhalte und ein Dialog mit einem größeren Fach- und Anwenderpublikum ermöglicht. Für eine inhaltliche Zusammenfassung in deutscher Sprache wird auf die Schlußbemerkung verwiesen.

1

Executive Summary

This document reports on the outcome of the project "Bewertungsmodul Klimapolitik" (BMK, Förderkennzeichen 03KSE041, May 2012 – December 2014) which is part of a broader and ongoing research process on green growth at the Global Climate Forum (GCF). In this process, we work on designing climate policy, particularly for Germany and Europe, that not only provides climate protection in the future but also offers immediate economic benefits. Based on several related research projects, GCF has outlined a win-win strategy for climate and the economy: investment-oriented climate policy can reduce emissions by about 50% (in 2030, compared to 1990 levels) and at the same time increase economic growth by about 8% and employment by about 2% in 2030 (compared to a reference case without climate policy).

The strategy is based on a green investment impulse for a decarbonization of energy production and other measures, most importantly a large scale energy efficient renovation of the European building stock. In providing a credible green growth perspective for Europe, investment-oriented climate policy can help solve a coordination problem of investors: profits of individual investors depend on whether they correctly estimate growth perspectives for the economy. These perspectives in turn depend on the expectations of the individual investors. In the current situation in Europe with low growth rates and low investment levels, that can be described as a "bad equilibrium", climate policies that increase total investment can combine the long-term benefits of avoiding climate damages with the short-term benefits of moving to a better equilibrium. A green investment impulse requires new incentives for additional private investment as well as training programmes for employees in sectors that implement it.

Last but not least, improved and new economic models for analysing investment-oriented climate policy are needed. Classical cost-benefit-assessments of climate policy focus on the effects of redirecting the existing investment volume towards green technologies and products through market based and regulatory instruments. Technically speaking, marginal analyses are carried out in the vicinity of a given equilibrium. This type of analysis is not sufficient for analysing the European "Energiewende" under conditions of slow recovery from the economic crisis: both issues call for substantial investments.

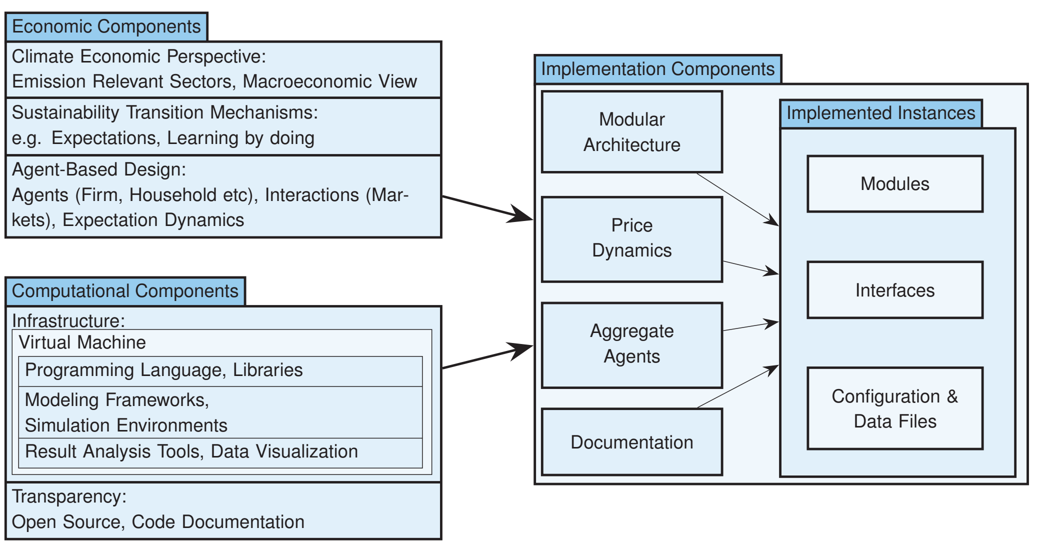
A European green investment impulse and its effects, such as the acceleration of technical progress induced by it, need to be analysed. A sustainability transition, at the technical level, is best described as a transition from one equilibrium to another – from the current, fossil fuel based growth path of the European economy to a green growth path. Such a transition is necessarily beyond the horizon of single equilibrium models. The green growth research process at GCF works towards cost-benefit analysis of investment-oriented climate policies by enhancing existing models and developing new ones in close interaction with stakeholders.

In particular, the goals of the present project were the following: to develop a module for assessing costs and benefits of German energy and climate policy measures in a macroeconomic context; to design the module such that it complements existing detailed sector specific models, based on a dialogue with experts and potential users; to provide the module as open-source software, and to allow for the identification of win-win strategies for climate policy by representing multiple equilibria in the module's structure.

The project outcome provides both less and more because the work to reach these goals proved to be more difficult, but at the same time more fruitful than anticipated. The agent-based module design which makes the consideration of multiple equilibria and out-of-equilibrium dynamics possible also meant slow progress towards a model for policy simulation. In fact, agent-based models that produce policy-relevant output close to real-world data are still rare. The model the project aimed at, successor of prototype and interim version presented in earlier reports, is not yet in a state where it could immediately be used for its ultimate purpose of assessing costs and benefits of climate policy measures in combination with sectoral modules. GCF will continue the development within its green growth research process.

In building this model, complementary work was necessary. For example, a simplified model was developed to help study mechanisms for out-of-equilibrium dynamics. Even though this work is not visible in the simulation macro-module itself, this model could not have been conceptualised, built, implemented, run, analysed, understood, etc. without it. The additional work can be helpful to other modellers and the scientific communities concerned with a sustainability transition (with green growth, a green economy, a low-carbon society, etc.) as well as climate policy analysis; it might even help bring these communities closer together. It should thus be accessible, not as a model, but as a framework for producing, coupling and using good modules in the cost-benefit-assessment of climate policy.

Figure 1: STOEMSys



This framework named STOEMSys – the Sustainability Transition Open Economic Modelling System – is presented in this report and displayed in Figure 1. It contains economic, computational and implementation components. The economic components are concepts relevant for understanding a sustainability transition. With a toolbox of computational components, these can be and have been combined to create implementation components such as modules or model building blocks, e.g., an implemented price dynamics library. STOEMSys can be extended, in particular with sector specific modules for climate policy analysis. As all its computer code is open source, it helps make scientific debates more transparent. STOEMSys agents are specified with resources, decision rules, a limited memory of past events, limited perception of present events and fallible expectations of future events. They interact via markets, where their expectations may be fulfilled or not; expectation dynamics thus drive market dynamics. This setup for out-of-equilibrium dynamics allows to study both marginal changes in the neighbourhood of a given equilibrium, as most economic models do, and inframarginal changes, in particular from an inferior equilibrium to a superior one. Thus, STOEMSys can be used to analyse climate policy measures for a sustainability transition.

Preliminary simulations within this framework support the finding that a green investment impulse can shift the economy to a new growth path with lower emissions but higher growth.

Part I

STOEMSys – Towards a Sustainability Transition Open Economic Modelling System

2 Introduction

The present report documents the outcome of the project "Bewertungsmodul Klimapolitik" (BMK, Förderkennzeichen 03KSE041, May 2012 – December 2014). Its tasks were:

- to develop a module for assessing costs and benefits of German energy and climate policy measures in a macro-economic context,
- based on a dialogue with experts and potential users, to design the module in such a way that it can complement existing detailed models of specific sectors,
- to provide the module as open-source software, and
- in the module's structure, to allow for the identification of win-win strategies for climate policy, via the representation of multiple equilibria.

According to the Energy Concept (Federal Ministry of Economics and Technology (BMWi), Public Relations, and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Public Relations 2010), Germany is "to become one of the most energy-efficient and greenest economies in the world while enjoying competitive energy prices and a high level of prosperity". This is possible only if win-win strategies for climate and the economy can be identified and implemented. Assessments of economic costs and benefits of climate policy that would point out such win-win strategies were virtually inexistent when the present project was initiated.[1]

The project has been part of a broader and ongoing research process on green growth at the Global Climate Forum (GCF), which analyses the question how climate policy, in particular for Germany and Europe, can be designed in such a way that it provides not only climate protection in the future but also more immediate economic benefits. This is done by enhancing existing economic models and developing new models in close interaction with stakeholders.

2.1 Investment Oriented Climate Policy for a Sustainability Transition

Based on several related research projects, GCF has outlined a win-win strategy for climate and the economy: investment oriented climate policy can at the same time reduce emissions by about 50% (by 2030, compared to 1990 levels) and increase economic growth by about 8% and employment by about 2% in 2030, compared to a reference case without climate policy (see, in particular, the forthcoming report "Investment-oriented climate policy – an opportunity for Europe" by GCF).

Decarbonizing energy production, providing the related infrastructure, increasing energy efficiency throughout the economy, restructuring transport systems, implementing related IT systems, and creating the system of vocational education necessary for a sustainability transition all require substantial amounts of investment. In the current European situation with low

[1] The Green Economy Report by United Nations Environment Programme (2011) could be viewed as a prominent exception, although its focus is much more general than climate policy.

growth and low investment levels, an investment surge of such kind is desirable also from an economic point of view. However, a coordination problem that arises in investment markets hinders such an investment surge: profits of individual investors depend on whether they correctly estimate growth perspectives of the economy. These perspectives in turn depend on the expectations of the individual investors in the economic system. Growth expectations are clearly low for Europe in the current situation.

In providing a credible “green” growth perspective for Europe, investment oriented climate policy can help solve the coordination problem of investors. A green investment impulse for a sustainability transition requires new incentives for additional private investment as well as training programmes for employees of those sectors that implement such an investment impulse. Finally, and most importantly in relation to the present project, it requires improved and new economic models for analysing investment oriented climate policy.

2.2 Analysing a Green Investment Impulse

Assessments of economic costs and benefits of climate policy mostly employ macroeconomic models to analyse the effects of climate policy redirecting economic resources (from fossil fuel based to green technologies) with the help of market based and regulatory instruments. This type of analysis is not fit for analysing the “Energiewende” under conditions of slow recovery from the Eurozone crisis: both issues call for substantial investments.

Technically speaking, marginal analyses are carried out in the vicinity of a given equilibrium. In this setting, standard model results suggest that climate change mitigation involves sacrifices in terms of economic development, ruling out win-win strategies for climate and the economy.

In order for climate policy to be successful, a transition from the current, fossil fuel based economy to a low carbon economic system is needed, as variously pointed out in the new, but growing literature[2] around “green growth” (e.g. Hepburn/Bowen 2012; Zysman/Huberty 2012). At the technical level, a sustainability transition seems best represented as a transition from one equilibrium to another one. For example, the two equilibria could be described as the current, fossil fuel based growth path of the European economy and a “green” growth path. Such a transition is necessarily beyond the horizon of single-equilibrium models. There thus is a gap between standard climate policy analysis models and the possibility of analysing a sustainability transition.

In particular, standard models for cost benefit analysis of climate policy measures consider the economy in the vicinity of the given situation. This single equilibrium in the model structure results from the use of representative agents, that is, the assumption that all agents of a given type have identical preferences and can thus be replaced by a single agent of each type. This does not leave room for modelling influences of agents upon each other, and hence there neither is room for studying coordination problems. Also, a green investment impulse would induce an acceleration of technical progress via learning by doing, that is usually not considered in standard models.

[2] This literature, found to a large extent in studies rather than journal publications, is mostly disconnected from the field of climate policy analysis, and modelling plays a secondary role. For an overview of approaches towards modelling green growth, see (Wolf/Schütze/Jaeger in preparation).

2.3 From the “German Green-Growth Module” to the Sustainability Transition Open Economic Modelling System (STOEMSys)

Before the just described background, the present project has worked towards the aims specified at the outset of this introduction. The results are, in a sense, both more and less than what was initially planned. A prototype and an interim version of a “German Green Growth Module" were already presented in previous project reports (Jaeger et al. 2013; Jaeger et al. 2014). From the outset, they were designed so that they could be combined with sectoral modules. This led to an in-depth effort to develop an open source agent-based macro-module with out-of-equilibrium price dynamics.

The point of using a modular architecture was to be able to combine sectoral expertise from different people and institutions with expertise on macro-economic dynamics, and to do so in order to assess costs and benefits of climate and energy policy measures. These assessments in turn should be useful to identify, enhance and implement win-win strategies in climate policy.

The requirement to represent multiple equilibira and thus allow for win-win strategies for climate and the economy made it necessary to think out of the (usual climate-policy simulation) box. Especially the need for having non-equilibrium dynamics means that trodden paths are being left. The choice of an agent-based module design, that makes the consideration of multiple equilibria and out-of-equilibrium dynamics possible, came at a price: Agent-based models, implementing agents on a computer with rules for interaction, and observing the system’s overall behaviour that arises from repeated interactions from simulation runs of the model, quickly become very complex (as is the modelled system, the economy). It is often difficult to understand observed overall system behaviour that arises from certain specifications of agents and interaction rules. This slows down simulation oriented work, and in fact, agent-based modelling exercises that produce policy-relevant output close to real-world data are still rare. The project work took account of this fact by starting from a hybrid between standard equilibrium models (growth models in particular) and agent-based models, identifying few agents within a growth model (in the prototype) and adding complexity in a step-by-step manner. However, implementing price dynamics based on expectations and learning into this simple model proved more difficult than expected. The model deriving from prototype and interim version is not yet in a state where it could immediately be used for its ultimate purpose of assessing costs and benefits of climate policy measures (in combination with sectoral modules, of course). That is, we do not supply one ready model with a button to choose German climate policies that, upon simulation, delivers the numbers of costs and benefits.

However, rather than just being more difficult, the necessary work towards the above goals proved to be more fruitful as well. For example, while working on the interim version, a simplified analysis model was developed in parallel, for understanding mechanisms that were then introduced into the simulation model. There is a trade-off between the simplicity needed to foster understanding and the amount of detail needed to reproduce real-world data, so that no single model can serve both purposes well. It thus became obvious, during the last project year, that both models should be further developed for their respective purposes.

Similarly, a lot of “supporting" work was needed that is not directly visible in the simulation macro-module itself, but without which this module could not have been conceptualised, built, implemented, run, analysed, understood, etc. This work can be helpful to other modellers and the scientific communities concerned with a sustainability transition (with green growth, a green economy, a low carbon society, etc.) as well as climate policy analysis – hopefully even conducive to bringing these communities closer to each other. It should thus be accessible, not only as a module for assessing costs and benefits, but as a framework with which to build useful models for assessing costs and benefits of climate policy, in particular for analysing investment oriented climate policy and the question how a green investment impulse can trigger a sustainability transition.

This framework is STOEMSys, the Sustainability Transition Open Economic Modelling System presented in this report. It contains a macro-module and a simple buildings module that are direct successors of prototype and interim version presented before. As part of the system, this particular model will be further developed beyond the project within GCF's green growth research process. In many respects, STOEMSys is very close to what previous project reports presented; but it has shifted the focus from a one-purpose fits all macro-module to a modelling system necessary for producing, coupling and using good modules.

2.4 The Structure of This Report

The report is divided into two parts: the first one presents STOEMSys before Part II summarizes supplementary project work.

Part I consists of eleven chapters:

Chapter 1 provides the executive summary, for readers with little time.

Chapter 2 introduces the practical problem of climate policy making and the related scientific problem of analysing climate policy, before (here) outlining the structure of the present report.

Chapter 3 outlines the research direction for cost benefit analysis of investment oriented climate policies, gathering (preliminary) results from several related research activities by GCF.

Chapter 4 summarizes the main challenges on the road towards identifying win-win strategies for climate and the economy in cost benefit analysis.To some extent the content of this chapter is also part of the project outcome because some challenges were not as clear beforehand.

Chapter 5 outlines STOEMSys, the main project outcome.

Chapter 6 describes economic components of STOEMSys.

Chapter 7 describes computational components of STOEMSys.

Chapter 8 describes implementation components of STOEMSys.

Chapter 9 presents the current state of analysis resulting from the current state of STOEMSys and points out further research directions.

Chapter 10 documents the successor of prototype and interim version, a model composed from a STOEMSys macro-module and buildings module.

Chapter 11 describes the calibration of this macro-module with buildings module model and documents the corresponding datafile.

Part II consists of three chapters:

Chapter 12 summarizes stakeholder dialogues that supported module development and were carried out via workshops, conferences and bilateral meetings throughout the project.

Chapter 13 summarizes sectoral analysis prepared to inform module development.

Chapter 14 summarizes a documentation of existing sectoral models prepared to inform the modular architecture of STOEMSys.

A conclusion of this report is given in Chapter 15.

3

Cost-Benefit Analysis of Investment-Oriented Climate Policies

The purpose of climate policy is to avoid damages from climate change. Therefore, the benefits of any given policy must include avoided damages. These damages, however, are notoriously difficult to assess. Moreover, most of them lie in a long-term future that despite forceful rhetorical declarations has rather little weight in the mechanisms of actual policy making. On the other hand, typical costs of climate policy are seen as occurring in a politically crucial short term. For example, a politically enforced carbon price will hinder markets to use technologies that otherwise would be most efficient in the short run. In this framing, climate policy becomes a sacrifice of welfare in the present to avoid even bigger losses of welfare in the future.

Most economic models currently used for assessing climate policies take this framing for granted. They are built in such a way that the economy follows an equilibrium growth path. This path is unique, stable, and optimal except for the long-term climate externality. This implies that in the short run the costs of any climate policy outweigh its benefits, and the more ambitious a policy is in terms of long-term climate protection, the bigger its short-term costs.

The state of many economies, however, and certainly of the economy of Europe, can only be understood as a “bad equilibrium” even in the short term (Draghi 2012). Therefore, the question of how to achieve a transition to a better equilibrium is vital both in its own right and in view of climate policy. Climate policies that ignore this problem risk to make things even worse than they already are. On the other hand, suitable climate policies can combine the long-term benefits of avoiding climate damages with the short-term benefits of moving to a better equilibrium.

In the following, four different simulations performed with four different models shall show that this is indeed a clear and present *opportunity for Europe*. Each simulation compares a business as usual (BAU) scenario with a green growth (GG) scenario. Under green growth, the system switches to a superior equilibrium, yielding lower greenhouse gas emissions while delivering higher growth. The green growth scenarios are based on investment-oriented climate policies, i.e. policies that do not simply direct the existing volume of investment towards green technologies and products, but rather increase total investment by moving in that direction.

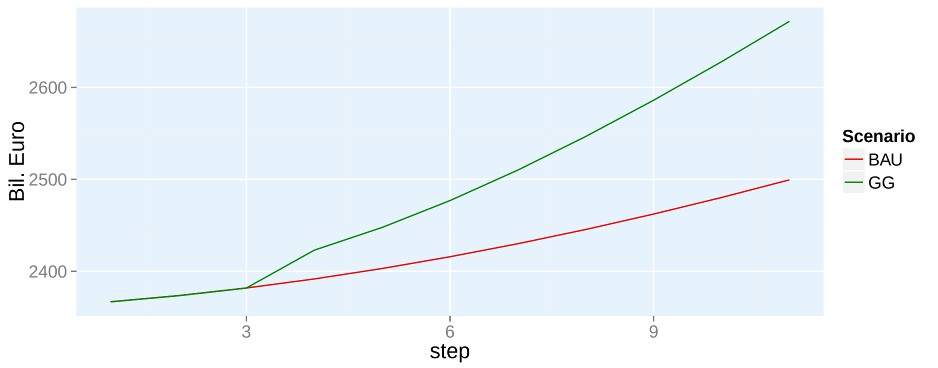
The point of STOEMSys is that it allows to identify such opportunities and to analyse them by implementing different models in a single modelling system.

3.1 A Simple STOEMSys Model

First, we compare a BAU and a GG scenario using a very simple STOEMSys model. Figures 2 and 3 display simulations of GDP and emissions. Clearly, any reasonable cost-benefit analysis will confirm that the green growth perspective is superior to business as usual.

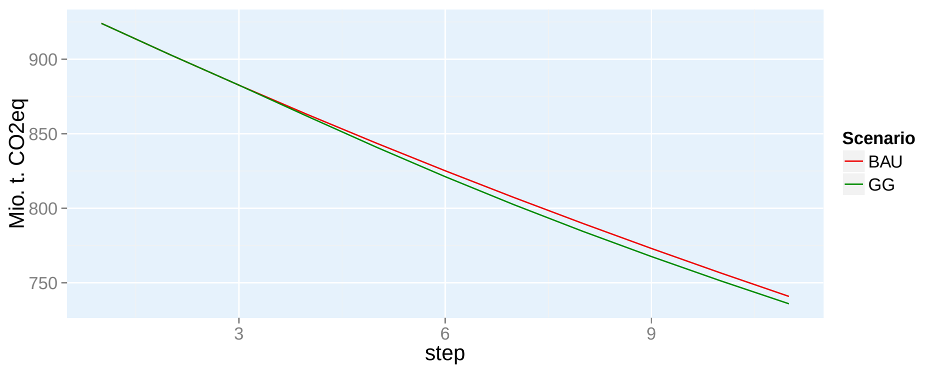
The model used here couples a sectoral module representing the building sector with a macro-module representing the rest of the economy. The macro-module consists of an aggregate household and an aggregate firm producing a “generic” good (or bundle of goods). The buildings module conists of two aggregate firms, a construction firm and a retrofit firm

Figure 2: GDP



Source: Own computation with a simple STOEMSys model.

Figure 3: Emissions



Source: Own computation with a simple STOEMSys model.

(transforming high emission “brown” buildings into low emission “green” buildings). All agents use very simple decision rules, as the purpose of this model is to single out underlying mechanisms, not to offer a comprehensive representation of the economy.

Here, the relevant mechanism is a policy that increases the retrofit rate from 0% of brown buildings in the BAU scenario to 3% in the GG scenario starting in time step 3. For the above simulations, the model was initialized with aggregate German economic data of the year 2010, and run for 10 steps, representing the years up to 2020. The level of GDP in the simulation results is stated in billion Euro, the same as for the input data used.

Because the built environment is the largest fraction of fixed capital, climate policies aiming at increasing its energy efficiency can be designed so as to trigger a significant increase in total investment, which in turn spurs additional growth.

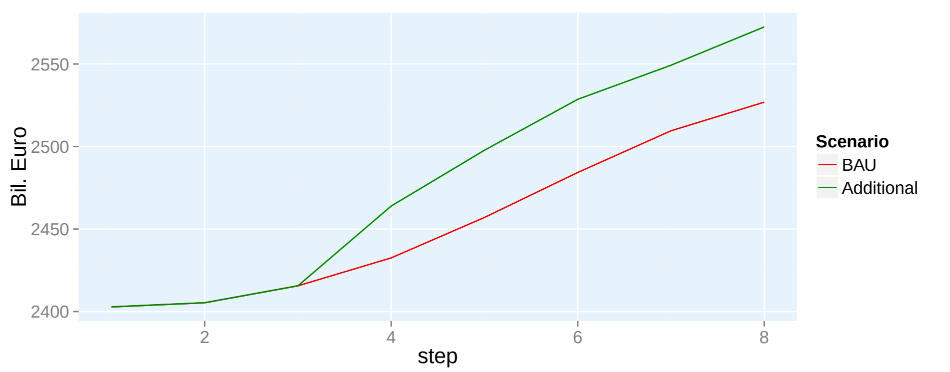
If one were to add a power sector into the model, emissions could be reduced much more, while preserving the higher growth path.

3.2 A Preliminary STOEMSys Model With Price Dynamics

Next, we again compare a BAU with a GG scenario, using a model with a similar multi-agent structure as in the previous section, but much more sophisticated decision rules. The reason for this lies in the fact that in transitions from one equilibrium to another prices cannot be in equilibrium all the time. Of course, in reality out-of-equilibrium prices are quite normal but it is remarkably difficult to model the dynamics of relative prices out of equilibrium (which is a main reason for the fact that most economic models do not model such dynamics at all).

Therefore, here we combine a macro-module and a buildings module with the same agents as above, but their decision rules have been refined: price dynamics driven by expectations that are updated with a learning algorithm have been introduced. More precisely, the generic firm in this version has expectations about the demand from the other agents at the prices it may set. By optimizing its expected profit it decides how much to produce and sets the price accordingly. When the market transactions have taken place, the firm uses the new information to update its expectations.

Figure 4: GDP

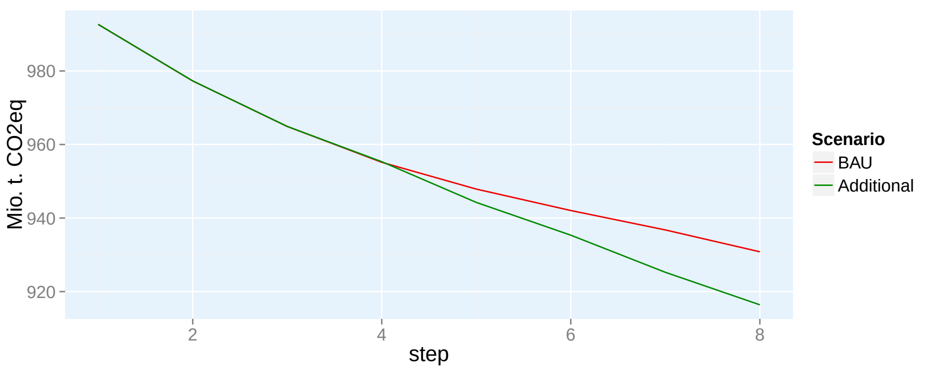


Source: Own computation, STOEMSys model with out-of-equilibrium dynamics. Preliminary.

Figures 4 and 5 display the preliminary results. They are preliminary in the sense that the model is still very sensitive to calibration changes and the observed dynamics show some problems after about a decade in the simulation (see Section 9.1). Also, with the price dynamics, the model needs a tuning phase at the beginning, not displayed in the figures, as the learning algorithm draws on results from previous time steps that have to be supplied artificially at initialisation. That said, as above, the simulation runs are initialised based on German aggregate data from 2010. A policy is introduced in time step 3, that increases the retrofit rate of brown buildings from 0% to 2% for households, which means that they make additional investments.

The modules are described in Sections 8.4.2 and 8.4.3, respectively, and the combined model is documented in Chapter 10. The great advantage of a modelling system like STOEMSys is precisely that it allows to improve different kinds of models stepwise, and to do so in a transparent manner.

Figure 5: Emissions



Source: Own computation, STOEMSys model with out-of-equilibrium dynamics. Preliminary.

So far, we have compared BAU and GG by using two multi-agent models. But the result that an ambitious climate policy can support a growth path that is superior to business as usual even with a short-run cost-benefit analysis does not depend on this model architecture. As the following two sections show, the result can also be confirmed by improving standard general equilibrium models so as to take into account a few well-confirmed mechanisms.

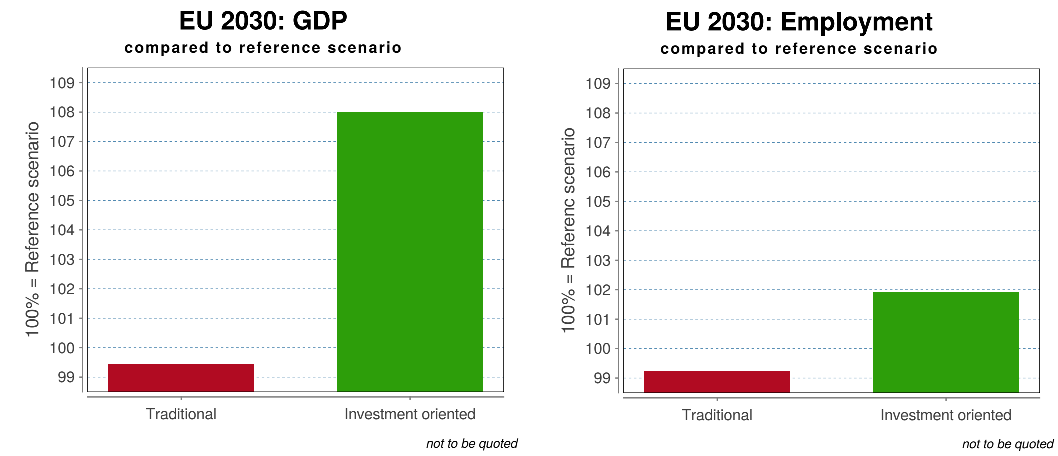
3.3 An Enhanced CGE Model

Computable general equilibrium (CGE) models are among the most widely used when it comes to assessments of economic and climate policies at the national level. In the EU, the most influential model of this kind is GEM-E3 (Capros et al. 2013), often used in conjunction with the energy system model Primes (Capros et al. 1999). In typical simulations, GEM-E3 considers learning-by-doing only for a few selected sectors of particular interest (like photovoltaics and wind energy). In reality, learning-by-doing happens across the board, however. An enhanced version of GEM-E3, developed in a separate project for the German Ministry of the Environment, takes this into account together with two more phenomena: the fact that labor markets rarely clear (and certainly not in Europe since the global financial crisis), and the fact that expectations change with economic conditions.

With this version of GEM-E3, we are presently performing simulations comparing a BAU and a GG scenario. A third scenario is included as well, namely the impact of a traditional climate policy focussed purely on the carbon price, in contrast to an investment-oriented climate policy needed for green growth. The preliminary results currently available are displayed in Figure 6. They look remarkably similar to those of the previous two sections.

The reference scenario does not suppose any climate policy targets, while traditional climate policy assumes a 50% emission reduction target (compared to 1990 levels). In addition to this emission-reduction target, the scenario for investment-oriented climate policy considers a 40% target for energy efficiency, investment incentives, technological progress accelerated by investment across sectors, and increased growth expectations.

Figure 6: GDP and Employment



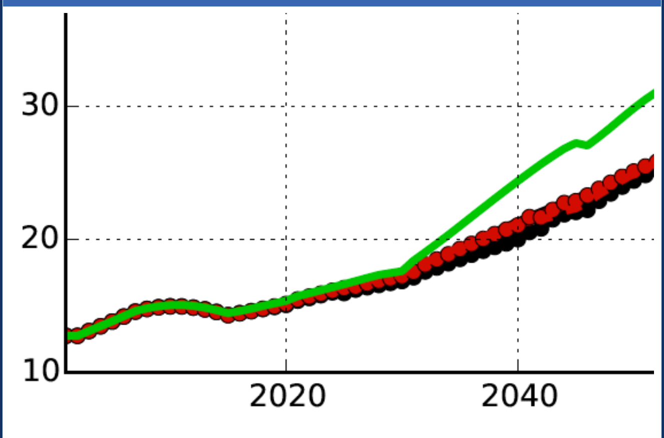
Source: Own computations in cooperation with E3M-Lab, March 6, 2015.

This line of work will be documented in the forthcoming report "Investment-oriented climate policy – an opportunity for Europe" by GCF. As the study is still ongoing, the results presented here are not for publication.

3.4 A Version of IMACLIM-WEM

Last not least, we compare BAU and GG scenarios with a sophisticated general equilibrium model that incorporates frictions and learning-by-doing in all sectors and regions, while capturing the role of expectations and financial crises via productivity shocks. The model IMACLIM (Cassen et al. 2010), developed at CIRED, Paris, is well established in the literature, for the present runs it has been combined with the energy sector model WEM of the International Energy Agency.

Figure 7: GDP growth



Source: Own computations in cooperation with CIRED. May, 5, 2015.

Figure 7 displays preliminary simulation results of GDP for three (hardly distinguishable) variants of BAU and for a GG scenario. Again, as the study is still ongoing, the results presented here are not for publication.

These four simulations, two with STOEMSys models and two with enhanced general equilibrium models show quite convincingly that in Europe for the coming decades a green growth perspective presents an opportunity that is vastly superior to business as usual. In terms of cost-benefit analysis, this means that on top of the long-run benefits coming from avoiding future climate damages there are short-run benefits to be reaped from the transition form a "bad equilibrium" to a better one. The remaining costs then are the transition costs. They are small in comparison with those resulting from single-equilibrium models, but they should of course be minimized by careful transition management.

4 Challenges

The practical challenge related to the analysis of costs and benefits of climate policy measures has been described above in the Introduction (Chapter 2): identifying win-win strategies for climate and economy, i.e. measures which not only reduce emissions but also induce economic benefits in terms of growth, employment etc. Such win-win opportunities arise when the economy manages to shift to a better growth path or, in more theoretical economic terms, to a different equilibrium. Section 4.1 considers the challenges of modelling multiple equilibria and non-equilibrium dynamics in the climate policy analysis context. As this requires new modelling approaches, another challenge common to modelling work is rather pronounced: the complementarity between simplified models for obtaining fundamental understanding and for analysing basic dependences, and models for policy simulation, which are able to reproduce empirical data. This is described in Section 4.2. One often justified criticism of many economic models is their lack of transparency with respect to the underlying equations and assumptions, which makes it impossible to understand or reproduce their results. Section 4.3 treats this topic.

4.1 Multiple Equilibria and Non-Equilibrium Dynamics

The state of the art of climate policy analysis modelling can briefly be sketched as follows. Computational economic models or so-called integrated assessment models, which combine an economic model with a climate model, are used to analyse the effects of climate policy measures. This is done by producing model runs for a so called business-as-usual (BAU) scenario without climate policy measures, and mitigation scenarios, in which mitigation policy is implemented. The comparison of these scenarios in terms of economic growth, jobs, welfare, or similar criteria then yields the costs and benefits of climate policy.

The basic structures of most commonly used model types derive from the framework of general equilibrium theory[3] in which they are grounded. Underlying ideas in general equilibrium economics are that rational agents optimize utilities or profits, as given by their preferences, taking prices as given, and that prices adjust to balance supply and demand, so that equilibrium is reached, i.e. all markets clear. This is formalized in the mathematical theory of general equilibrium as developed by Arrow/Debreu (1954). The theory shows that under certain conditions economic equilibria exist and that these are Pareto optimal, i.e. no agent in the system can be made better off while all others stay at least at the same level. The theory also shows that equilibria are generally not unique, and none of the possible equilibria is predetermined to be the one that should prevail in a given economic system. In fact, the theory does not provide mechanisms for the dynamics of economic systems, or for equilibrium selection. A system of equations is solved simultaneously to find those prices at which equilibrium is obtained, together with the respective quantities. The commonly told story of the auctioneer who reduces prices of goods for which there is excess supply and increases those of goods with

[3] While general equilibrium theory has been widely criticised, especially since the financial crisis, no other approach has as yet been able to replace this overarching paradigm in economics.

excess demand until equilibrium is reached does not actually translate into price dynamics for the formal system, that starting out from a given state would lead the system into equilibrium. Many mechanisms for price dynamics have been studied but none has been found that would work reasonably well for a reasonably large class of economic systems (see Saari 1995).

Two types of computational models that are very prominent in climate policy analysis, computable general equilibrium (CGE) and optimal growth models, are based on these ideas without strictly being implementations of the formal general equilibrium system. Both model types use representative agents, an assumption which reduces the number of possible equilibria to a single one in the general equilibrium framework (for a critique of the representative agent see Kirman 1992). The problem of equilibrium selection is thus beyond the horizon of these models.

The focus of optimal growth models is the allocation of a produced good in each time step (often considering an infinite time horizon) between consumption and investment in such a way that a representative household's lifetime utility – defined as an (infinite) sum of the discounted utilities derived from consumption at each time step – is maximized. CGE models add an optimization for the allocation of resources to different sectors using input-output tables at each time step to a similar inter-temporal optimization structure for capital.

In both cases, the business-as-usual scenario is computed as an optimal trajectory of the system in the absence of climate change mitigation policy. Climate policy then enters as an additional constraint for the mitigation scenario, meaning that by definition the result can at most be as good as the BAU case, and usually comes out "worse". Within the given structure of the economy, provided by the single equilibrium that is being considered, the focus is on marginal changes induced by climate policy. In other words, the analysis focuses on climate policy redirecting economic resources (from fossil fuel based to green technologies) with the help of market based and regulatory instruments. As it is obvious that a sustainability transition involves non-marginal changes to the economic system, modelling multiple equilibria and transitions from one to another equilibrium is essential for investigating costs and benefits of an investment oriented climate policy that aims at such a transition. The challenge of multiple equilibria has been pointed out, but has not then been addressed, in the context of the "National Energy Modelling Sytem" (NEMS) of the USA.[4]

As discussed above, CGE and optimal growth models are – in contrast to general equilibrium theory – restricted to a single equilibrium. There is no out-of-equilibrium dynamics defined but the usual assumption is that for small deviations the system will return back to equilibrium immediately. While there is same empirical evidence for the state of the economy being quite stable over time (sudden price jumps are not usually observed), however, there is no theoretical foundations why equilibria obtained by these modelling approaches have to be stable and for how large a deviation from the original state the system may not come back to it (see Saari 1995). For modelling an economic transition (theoretically a transition between two different equilibria) that means that the modelling system has to provide an out-of-equilibrium dynamics, which can not relay on the well-understood framework of general equilibrium theory.

[4]Quotes and refs: searching for multiple equilibria, until it is determined that multiple equilibria do exist or until confidence is gained in the idea that the equilibrium is unique. . .

4.2 A Complementarity Problem: Understanding the Principles Versus Simulating Real-World Economies

Models are used in economics for at least two purposes: analysis of the principles of economic interdependencies and simulation of different policies. The spectrum of models used ranges from theoretical, mathematical models possibly given by a few equations with economic interpretations to computational simulation models drawing on large databases and producing output in very many dimensions. Generally speaking, models for analysing more fundamental economic problems may tend more towards the theoretical end of the spectrum, while models for simulating real-world economies are almost necessarily much more complex computer models. These two motivations for building models are complementary in the sense that there is a trade-off between the simplicity needed to foster understanding and the amount of detail needed to reproduce real-world data. This means that no single model can serve both purposes well at the same time.

Often, computational models are based on theoretical insights (as described above for the general equilibrium framework and CGE or optimal growth models), and the theoretical assumptions they build on are taken for granted. Standard economic models can draw on a rich theoretical literature about the fundamentals they are based on.

However, as will be further detailed below (Section 6.4), the modelling approach chosen here is an agent-based design of the economy. Agent-based models (ABMs) present a relatively new approach to studying the macro-level behaviour of economic systems as arising from action and interaction of agents at the micro-level. This is done by computer simulations. An ABM implements agents at the micro-level on the computer, equipping them with rules for (inter)action. Simulation runs are then used to study the evolution of the system at the macro-level (see, e.g. Tesfatsion/Judd 2006). In particular in the context of the recent financial crisis, a need for agent-based modelling in economics has been stated (e.g. Farmer/Foley 2009). Building agent based models for policy simulations may thus seem straightforward: represent the actors involved with their essential actions, interactions, expectations etc. as agents, and run simulations. However, starting from a real-world question it is often by no means clear what these essentials are, and observed system behaviour in the model may differ largely from observed real-world data. There are thus two tasks to be solved at the same time: simulate real-world phenomena and understand how mechanisms and modelled dynamics work.

For the second of these tasks, no theoretical background can be taken for granted. ABMs provide the modeller with great freedom of representing agents behaviour. Bounded rationality, imperfect knowledge, heuristics as decision rules and other features can be included without compromising the solvability of a closed form model, simply because there is no such model. However, this freedom also comes with a downside: many similar and yet differing ABMs are being built in an ad hoc mode, and economic ABMs in particular are often rather complex models. There is no commonly accepted theoretical basis that these models build on and no common language for describing them, let alone to analyse and compare them. The non-existence of closed form models also means that theoretical analysis of such models is not available as a tool for understanding the model's dynamics etc. It may thus often be difficult to understand the observed system behaviour resulting from specific model configurations at the level of agents. The enormous freedom of modellers when building ABMs of what to represent and how, means that there are myriads of mechanisms and modelled dynamics to be analysed and understood. This challenge has been met by extending the project work from the task of building a simulation model to building an open economic modelling system that includes different models for the different purposes of problem analysis and policy simulation.

4.3 Transparency of Economic Modelling

Economic models in mathematical form can be shared by publishing equations and text. Often, models for understanding principles are relatively small, making this a transparent form for scientific exchange.

In principle, simulation models could be shared by publishing the computer code that implements these models. However, policy-simulation models that often many people have worked on over longer periods of time are generally rather complex. In fitting data, many small ad hoc extensions may be made to a core model, that clutter the model code. While sharing such code is necessary for a transparent basis of scientific exchange – let it be said that model code is almost never publicly available in economic modelling for policy simulation – it is hardly sufficient, revealing the importance of model documentation.

Good model documentation, however, is a challenge in itself. For ABMs in particular, it is described extensively in the Dahlem ABM documentation guidelines (see Wolf et al. 2013a): it is not so clear what exactly is the model, between an idea in the head of the modeller, and the code implementing it. Different documentations would be needed for different audiences, for example model users and model developers; different elements in an ABM seem to require different forms of description (mathematical, computational such as pseudo code, etc); and while ABMs could in theory be described as dynamical systems it is generally impossible to write down state and transition function of the system in closed form. The challenge may be a bit less pronounced for some other model types, but complex computational models are never easy to document well. System dynamics models have large numbers of equations which refrain modellers from publishing the complete set of equations, CGE model documentations are often inaccessible to anyone but people who are very familiar with CGE models, to just name some examples.

For transparent scientific exchange about results obtained from simulation runs with computational models, in addition, all parameters and input data for obtaining these simulations would need to be known (see, e.g. Rosen/Guenther 2015 on this topic). All this points to the fact that more transparency in climate policy analysis modelling would lead to a new quality of the scientific debates in climate economics.

5

What STOEMSys Is

To address the challenges described in Chapter 4, a Sustainability Transition Open Economic Modelling System (STOEMSys) has been developed. This section offers a brief outline of STOEMSys, before Chapters 6, 7 and 8 describe its building blocks in more detail.

A **sustainability transition** is the system's focus because, as was outlined in Chapters 2 and 3, climate policy can only be successful if it manages to trigger a transition of the economy, from the current fossil fuel based growth path to a green growth path.

It is an **open** system in two respects: First, STOEMSys is designed to be extended by additional components, in particular by complementary modules, including specific third-party sectoral models. Its modular architecture is geared towards complementing a macro-economic module with information from detailed models of specific climate-relevant sectors, in order to strike the right balance between sectoral considerations and the macroeconomic "big picture" for assessing effects of climate policy. Second, we are committed to transparency in our modelling work and thus prepared to reveal all the assumptions implicitly used in the way how the software is implemented. Therefore, all STOEMSys computer code is open source and is freely available upon request.

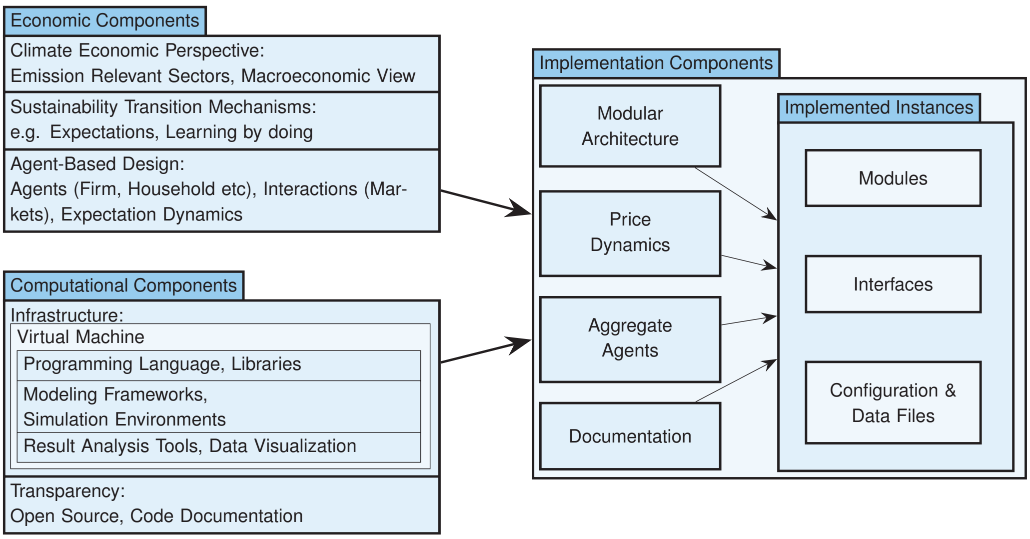
It is an **economic** modelling system aimed at evaluating costs and benefits of climate policies. The system is designed in a way that these can not only be reported in monetary terms but also in non-monetary terms with explicit reference to particular agents (e.g. unemployment, GHG emissions, etc.).

Finally, STOEMSys is a **modelling system**: it is not a ready made simulation model that, upon the choice of some climate policy measures, via clicking a button, delivers numbers of costs and benefits. What it provides is a variety of different tools for tackling the task of producing economic simulations of a sustainability transition. It thus is a framework of elements necessary for producing such models, that shall – in contrast to standard climate policy analysis models and via the representation of multiple equilibria which these do not provide – be able to identify win-win strategies for climate policy. This requirement made it necessary to think out of the (usual climate policy simulation) box; the main challenges have been pointed out in Chapter 4. Especially the need for non-equilibrium dynamics means that trodden paths are being left. The new direction of results STOEMSys can provide has been contoured in Chapter 3.

Figure 8 displays the modelling system at a glance. It has three types of components:

- **Economic components** of the modelling system are the elements of the economic system and the concepts relevant for analysing a sustainability transition. Three groups of such concepts have been identified. *Mechanisms for a sustainability transition* include investment leading to learning by doing, leading to accelerated technological change, and the roles of expectations, or of coordination in influencing the state of an economic system. A *climate economic perspective* implies that it is necessary to balance a focus on details of emission relevant sectors with an overall macroeconomic view. An *agent-based design*, including agents such as firms, households, a government etc., and their

Figure 8: STOEMSys



Economic, computational, and implementation components

interactions in markets, accomodates the fact that the economy is a complex evolving system of many heterogeneous agents in interaction. A description of the economic concepts can be found in Chapter 6.

- **Computational components** of the modelling system provide a sort of toolbox for working with models to analyse a sustainability transition. All STOEMSys code is *open source* as a quality standard for working towards transparency. Some of the computational tools provided by STOEMSys constitute an infrastructure for implementing agent-based models on a computer: a *system language*, an *economic type system* that increases both the readability of programmes, essential for the open source property, and the software quality, a *framework for agent-based modelling* provides, e.g., a graphical user interface. *Post-processing and visualization* tools provide an infrastructure for observing results when running models. A *rapid prototyping framework* plays both these roles for quick testing of new ideas. All the above can be assembled into a *virtual machine*, to provide the computational framework of STOEMSys for working on different pieces of hardware that use different operating systems. Details can be found in Chapter 7.

- **Implementation components** are what is created to represent the economic components using the computational framework. A *modular architecture* implements the climate economic perspective: sectoral modules describe emission relevant sectors in as much detail as necessary while a macro-module provides the macro-economic context, e.g., in form of implementations of labour and financial markets. *Price dynamics* based on expectations and learning implement mechanisms for a sustainability transition. *Aggregate agents* are used to keep implemented modules simpler in a first phase. STOEMSys models consist of *modules*, possibly with *interfaces*, and *data- and configuration-files*. Different macro-modules are available as an approach to the complementarity problem (see Section 4.2). Each agent in a model can be attributed to one of the modules, as can each market. Interfaces for coupling sectoral and macro-modules are provided by the markets in which interactions between agents (and hence between modules) take place. Data- and configuration-files allow the model user to initialise a model to represent a certain economic system at a certain point in time. Finally, the *documentation* – of a model as a conceptual entity as well as of the code – is an implementation component of STOEMSys. This is an essential one, as the level of transparency in assessing climate policy analysis should be maximal to improve the quality of the scientific debate. The Implementation components are the described in more detail in Chapter 8.

Summarizing, STOEMSys is adapted to analysing the “Energiewende” under conditions of slow recovery from the Eurozone crisis as its agents – equipped with resources, decision rules, a limited memory of past events, limited perception of present events and fallible expectations of future events – interact via markets, where their expectations may be fulfilled or not. STOEMSys does not require the modelled economic system to be in any kind of market equilibrium; expectation dynamics drive market dynamics. This setup for out-of-equilibrium dynamics allows to study both marginal changes in the neighbourhood of a given equilibrium, as most economic models do, and inframarginal changes, in particular from an inferior equilibrium to a superior one.

6 STOEMSys Economic Components

Cost-benefit analysis of climate policy presupposes both a *focus on emission relevant sectors* in the economy and a *macro-economic view* that captures system-wide effects and impacts in macro-economic terms, such as GDP growth, employment or inflation. Identifying *win-win strategies for climate and the economy* requires the consideration of *multiple equilibria* and the study of *mechanisms by which climate policy can induce a transition from the current fossil fuel based economy to a sustainable, "green" economic system*. Expressions printed in *italics* in the previous two sentences are economic building blocks of the STOEMSys, in the following sense.

Economic components of the Sustainability Transition Open Economic Modelling System are those elements of the economic system relevant for modelling and analysing a sustainability transition. Here, "elements" is to be understood in a broad sense, with examples ranging from goods and agents in the economy to markets and bounded rationality and equilibrium selection dynamics. While goods and agents seem more tangible concepts, markets and bounded rationality appear a bit more abstract, and equilibrium selection dynamics have a decisively theoretical touch, even a "good" is abstracted from the many varieties of things relating to what is modelled as this "good" that one finds in the real world. One could thus also rephrase "elements of the economic system" as "concepts used in economics". In this case, some concepts are more basic (e.g. a firm or a household), others are defined upon more basic concepts (e.g. equilibrium, that obtains when markets clear, that is supply equals demand, with supply and demand in turn defined upon firms' and households' actions and wishes). For the more involved of these concepts, "building blocks of economic thinking and theory" may be a more intuitive description.

This section lists and explains elements of the open economic modelling system. Given that it is an open system, the list is not set in stone: further work towards modelling and analysing a sustainability transition may reveal that further elements are needed, or make some elements presented here obsolete. Also, elements that appear only in the description of concepts listed here might, with further development of the STOEMSys, turn out to be so important as to merit a list entry of their own.

6.1 Mechanisms for a Sustainability Transition

6.1.1 Investment and Learning-by-doing

A sustainability transition requires serious emission reductions, which in turn require large amounts of investment for decarbonizing energy production, providing the related infrastructure, increasing energy efficiency throughout the economy, restructuring transport systems etc.

As pointed out in Chapter 2, climate policy can help coordinate investor's expectations for a sustainability transition. Before considering expectations (see 6.1.2) and coordination problems (see 6.1.3), as two important concepts here, in some more detail, we need to point out an (indirect) effect of investment, that is often disregarded in climate policy analysis modelling: the acceleration of technical progress.

A green investment impulse would not only have the direct effect of increasing capital accumulation but also an indirect effect: increases in efficiency are to a large part due to learning by doing, and such learning happens mostly via the introduction of new equipment (i.e. investment). In an aggregate model of production that considers both capital accumulation and learning by doing as mechanisms behind economic growth, meaning that investment drives growth both directly and indirectly, multiple growth paths based on investment can be observed. It is hence considered important for models in the STOEMSys to carefully represent influences of investment on technological change.

6.1.2 Expectations

Investment is also the point where expectations come into play: While investors may be interested in rates of return and the like, they need to take their investment decisions under uncertainty so that the decisions are necessarily based on expectations. To analyse how climate policy might influence such expectations for triggering a sustainability transition, modelling expectation dynamics is of major interest.

Different growth patterns in the past have shown that investment dynamics can be considered as a case of convention dynamics[5] with several focal points for investors' growth expectations. In a setting of low growth, agents expect further low growth and invest little, while in periods of higher growth, expectations improve and hence investments increase. In both cases the dynamics is self-perpetuating, that is, the focal point of investors' expectations is likely to stay in place. However, looking at the history of economic growth, there have been shifts from one focal point to the other and back, that is, transitions from one convention to another are possible. Relating back to the challenge of multiple equilibria described in Section 4.1, the self-fulfilling property of expectations has also been pointed out in a description of Europe's situation by the president of the European Central Bank, M. Draghi: “we are in a situation now where you have large parts of the euro area in what we call a 'bad equilibrium', namely an equilibrium where you may have self-fulfilling expectations that feed upon themselves and generate very adverse scenarios” (Draghi 2012).

The role of expectations in selecting a convention (an equilibrium) out of several viable alternatives needs to be analysed and incorporated into simulations for analysing a sustainability transition. Feedbacks between agents' expectations that may lead to self-fulfilling dynamics can be modelled using an agent-based approach (see Section 6.4).

[5]Conventions arise in cases where groups of people can choose between several alternatives, but benefit from coordinating on the same choice. A standard example is driving on the right or left side of the road. Convention dynamics show long stretches of time where one of the alternatives is chosen – it becomes the conventional way of doing things – but sometimes, a transition to another alternative may occurr. Such transitions usually take place rather quickly, by a critical mass of group members switching to the new convention, since times where several alternatives are used within the same group of people are usually problematic.

6.1.3 Coordination

Given that we have described the practical challenge for a sustainability transition as a coordination problem of investors' expectations, this concept is also part of economic building blocks of STOEMSys.

Profits of individual investors depend on whether they correctly estimate growth perspectives of the economy. These perspectives in turn depend on the expectations of the individual investors in the economic system. This means that no agent in the economy can make the transition to a green growth path alone, but all could benefit from a coordinated shift to it.

Jaeger 2012 analyses climate policy as an example of problems of the global commons and points out that equilibrium selection is a coordination problem. He summarizes that markets are multistable systems with a major difference between marginal changes, for which price movements operate as scarcity signals, and regime changes, for which prices are conventions that solve a coordination problem, and highlights that regime changes in which these conventions are modified need to be investigated in a perspective of sustainable development [see p. 97].

Considering climate change a market failure "whereby the uncoordinated actions of individuals pursuing their own self-interest collectively deliver a worse outcome for society as a whole" [p. 9] as Zenghelis 2011 puts it, suggests that framing the question under study as "how can climate policy facilitate a re-coordination of investors' expectations for a sustainability transition?" is helpful for modelling and analysing costs and benefits of climate policy.

6.2 Climate-Economic Perspective

The climate economic perspective of the STOEMSys presupposes a focus on emissions. These are distributed unevenly throughout the economy, and potential measures for reducing emissions differ substantially between sectors, for example between measures for reducing the emission intensity of energy (meaning less emissions per unit of energy) and those for increasing energy efficiency (meaning that less energy is used). Any analysis of measures taken to reduce emissions needs to take into account "bottom-up" analyses of sectors like energy and transport, buildings, and production processes (see Chapter 13 for results from sectoral analysis of the present project).

However, policies targeted at a specific sector will also have cross-sectoral, labour market or other macro-economic effects. A macro-economic view is thus necessary for analysing effects of climate policy, be it in the form of an assessment of costs and benefits or for analysing a sustainability transition, which concerns the whole economic system.

The macro-economic view has two aspects to it: on the one hand, sectors or parts of the economic system of which a detailed analysis is not necessary for climate policy analysis can be summarized under "the macro-economy" to keep the system as simple as possible. On the other hand, and probably more importantly, there are agents of economic systems that are usually not considered part of any given sector: households, a government, a central bank etc, the same is true for the labour market (with which agents from all sectors interact). Some indicators of the economic system's development, such as GDP, employment, price-level, interest rate, and money supply (see, e.g. Keynes 1936) describe its macro-economic evolution of a system. This arises from the interactions of sectoral and non-sectoral agents in the economy.

As climate policy analysis is interested also in effects of climate policy on these indicators, a macro-economic view needs to complement sectoral considerations.

6.3 Metrics for Costs and Benefits

Climate policy analysis is often framed in terms of assessments of costs and benefits of certain policy measures. Since in particular the term "costs" has a monetary connotation, it shall be briefly mentioned here that it is an explicit aim of STOEMSys to consider "costs and benefits" of climate policy, in particular those of investment oriented climate policy by triggering a sustainability transition, also in non-monetary terms with explicit reference to particular agents (e.g. unemployment, GHG emissions, etc.). In particular, a wide range of model outputs to be observed with the help of elements from the computational infrastructure and toolbox presented in Chapter 7 for the different implementations presented in Chapter 8, allows to consider a multitude of effects of climate policy, that can then be considered "costs" or "benefits" of it.

6.4 Agent-based Design

Investments for a sustainability transition need to be provided by very many actors in the European economy, so the question is how climate policy can convince many individual and corporate investors to invest into a greening of the economy, rather than using the same resources in financial markets, for consumption, for investment into a business as usual economic system, or else. With the related coordination problem and the importance of expectations described above, this means that the economy needs to be considered as a complex system consisting of many heterogeneous agents. To be able to incorporate the above described important mechanisms lead to the choice of an agent-based design of the modelled economy within the STOEMSys.

This means that in a given model, agents are implemented with certain rules for (inter)action, and the economic system's development as resulting from actions and interactions of the agents computed in model runs. In the following, agents and their interactions are described. The remainder of this section is to be understood as a conceptual basis for an agent-based economy in STOEMSys, not all of the agents and interactions are present in the current state of the implementations in Chapter 8.

6.4.1 Agents

Agents are specified with their resources, decision rules, a limited memory of past events, limited perception of present events and fallible expectations of future events. Generally speaking, agents in the STOEMSys can be characterised as boundedly rational and myopic, in contrast with the rational and omniscient agents in many standard economic models. They take their decisions using rules of thumb, based on past observations and expectations.

6.4.1.1 Firm

Firms produce goods and sell these. They belong to sectors, in particular, they may belong to an emission relevant sector that is considered in detail, or to "the macro-economy" (see Section 6.2).

The production process requires (some of) the following inputs:

- fixed capital, possibly from all sectors: machines, buildings, etc, anything that is not used up in the production process. Fixed capital depreciates by production, or simply by time going by. Infrastructure is another form of fixed capital. Some firms have a high share of infrastructure (e.g. the German Railways) others have a low share and rely on other firms providing it (e.g. power generators).
- intermediary inputs, possibly from all sectors and the environment: anything used up during the production process.
- labour: offered by households.

Outputs from production are goods and emissions. Technologies specify the inputs needed and their efficiencies for producing one unit of the output good, as well as the amount of emissions this causes. Formally, the transformation of inputs into outputs can be described by a function f of the following type (using the types described in Section 7.3 below), the production process is given by as follows

$$\begin{aligned} f : \mathit{GoodsAmount} \times \mathit{GoodsAmount} \times \mathit{Labour} &\rightarrow \mathit{Goods} \times \mathit{Emissions} \\ (\text{fixed capital, intermediary inputs, labour}) &\mapsto (\text{goods, emissions}) \end{aligned}$$

Firms are characterised by a stock of fixed capital, their financial situation, a set of possible technologies, which are in turn characterised by efficiencies evolving over time, and decision rules. As they do not have perfect foresight, they have expectations about things they do not know but need to base decisions on: the demand for their produced good, prices and supply of goods, the supply of labour in the markets, etc.

Based on a decision rule, a firm decides how much to produce according to each of the possible technologies, the amount of wage to pay for a unit of labour and the price at which to sell the produced goods. These decisions require amounts of labour, capital, and intermediary inputs, and hence (given capital and labour) the amounts of investment and employment required. Firms try to buy the required goods and employ labour, having to take the supply in these markets and prices of goods as given by other agents. They may borrow money to finance their requirements. The financial situation is updated accordingly.

Having bought goods for fixed capital and intermediary inputs, and employed labour, they produce. The technologies with the actual efficiencies determine the outputs. Produced goods can then be sold, where the market demand met (at the price that the firm has set) determines the quantities sold and the revenues thus obtained. Together with the costs incurred for production (possibly including interest to be paid as resulting from their financial situation), these determine the firm's profits.

The efficiency parameters of technologies may evolve according to the system's evolution, for example, efficiencies may increase with aggregate investments in the corresponding sectors, due to learning-by-doing effects.

Expectations are updated according to experience: prices paid, quantity sold, etc. Further, expectations may be influenced by other agents' recent actions (e.g., a policy set by the government), and aggregate characteristics of the system, such as growth, employment, or the aggregate capital stock.

6.4.1.2 Household

Households supply labour, consume goods, pay taxes, may own firms etc. Also, households represent the demographic evolution in the economic system. They are an element of the macro-economic view on the economic system. They may play an important role in tipping the economic system from the current growth path onto a green growth path, for example by making choices about which goods to consume. In particular, imitation or social pressure can create feedback effects. Such phenomena can be modelled by making a household's decisions (for example to buy electricity from renewable resources instead of from fossil fuels or nuclear) depend, for example, on the decisions taken by neighbouring households or on the average decision of all households.

Similarly to firms, households have expectations about those aspects of the system that they do not know: prices they will find in the market, wages that employers are willing to pay, the efficiency of certain technologies, etc. These are updated according to experience and observations of other agents.

Households have a consumption "technology" that specifies the amounts of goods they want to consume from each sector. They may gain utility from consumption, and their decisions can be based on aiming at high levels of utility, as based, in turn, on expectations.

They can invest into fixed capital, particularly from the construction sector (i.e., buildings). This investment may influence the efficiency of the consumption technology, e.g. to represent that a building (in which a household lives) has been retrofitted.

6.4.1.3 Government

The government plays two main roles in the model: it sets climate and energy policies and it is an agent in the economic system. Since policy measures are assessed by STOEMSys modules, these will be provided as inputs, so that a model user can choose from a set of policies in order to analyse effects of certain measures.

The government agent in the modelled economy thus represents the government as an economic agent that creates demand and employment, invests into infrastructure, collects taxes, etc. This means that the government has some characteristics of a firm, such as fixed capital and employees, however, it does not produce and sell a specific good.

6.4.1.4 Financial System

The role of the financial system is to provide loans to businesses via savings from households and firms ("money middleman"). Formally, this fact is given by a function g:

$$\begin{aligned} g : \mathit{MoneyAmount} &\rightarrow \mathit{MoneyAmount} \\ \text{savings} &\mapsto \text{loans.} \end{aligned}$$

It sets the interest rates which it pays to lenders and charges from borrowers. Since most renewable energy projects are to a large extend (up to 90%) financed by debt, available loans are important for the expansion of the renewable energy sector.

Further, in the climate policy context, a financial systems agent need to be considered as a provider of financial instruments targeted at climate protection (climate finance), examples could relate to a green fiscal stimulus or green quantitative easing.

6.4.1.5 Rest of the World

To consider imports and exports, the rest of the world has to be represented as a trading partner in the model. This means, that the rest of the world agent can buy goods and financial assets from all sectors (export) and sell goods and financial assets to all sectors (import). In terms of economic types, this correspods to $h : \mathit{Goods} \times \mathit{FinancialAssets} \rightarrow \mathit{Goods} \times \mathit{FinancialAssets}$.

6.4.2 Interactions/Markets

Interactions between agents take place in model runs in agent-based models. For STOEMSys implementations (see Chapter 8), for now, interactions take place in markets for goods and labour (other interactions could concern imitation of characteristics between agents, for example). Markets are characterized by a list of sellers and a list of buyers, who each enter the market with a (supply, price)-, respectively (demand, price)-information, representing the amounts desired to sell/buy and the respective ideas about prices. Formally, a market corresponds to a function that matches sellers with buyers and transforms these tuples of information into the amount traded and the price at which it is traded.

6.4.2.1 Goods Markets

In goods markets, goods produced in the economy are traded. Households and the government buy goods for consumption. Firms sell the goods they produce, and buy both fixed capital and intermediary goods from each other. Goods are also exported and imported to the rest of the world.

6.4.2.2 Labour Market

At the labour market, households are the “sellers" (rather referred to as applicants), while firms and the government act in the role of “buyers” (rather employers). The price for labour is referred to as wage.

6.4.2.3 Capital Market

The market for capital organizes the allocation of capital in the economy. The financial sector acts as a “middleman” by lending money (*MoneyAmount*) to firms which need financial capital to invest in fixed capital for production. Households and firms save money on their bank accounts.

6.4.3 Dynamics via Expectations and Learning

As was described, agents interact via markets, where their expectations may be fulfilled or not. Based on observations made, agents update their expectations, or in other words, learn. For details, see Section 8.3. Expectation dynamics thus drive market dynamics. This setup for out-of-equilibrium dynamics allows to study both marginal changes in the neighbourhood of a given equilibrium, as most economic models do, and inframarginal changes, in particular from an inferior equilibrium to a superior one. For analysing the “Energiewende” under conditions of slow recovery from the Eurozone crisis, this is an essential feature.

7

STOEMSys Computational Components

An important element of any computer model is its source code. All STOEMSys code is open source, considered a necessary, albeit not sufficient, condition for the transparency of the scientific debate that STOEMSys wants to foster. To flag the importance of the open source property, it is listed as a computational component of the system, and the related questions concerning licensing are discussed in Section 7.1.

In order to build and work with computational agent-based models, an infrastructure of computational tools is needed. These are further computational components of STOEMSys: tools for implementing agent-based models comprise a system language (Section 7.2), an economic types library (Section 7.3), and a framework for agent-based modelling (Section 7.4). Further tools are needed for observing and analysing model outputs. Here STOEMSys supplies several components for post-processing and visualization (Section 7.5). Besides this full fledged framework, a rapid prototyping framework for quick testing of new ideas is provided (Section 7.6). This toolbox can be assembled for ready delivery in a virtual machine (Section 7.7), that provides the possibility of using it independently of the operating system present on the computer it shall be used on.

7.1 Open Source Code

A goal of the present project was to develop a modelling system that complements existing sectoral specific models. This demands a careful selection of the licence for the delivered components. Inspired by the success of open source software in the last decades, an open science movement emerged which pursues the following goals (see Gezelter 2009):

- Transparency in experimental methodology, observation, and collection of data.
- Public availability and reusability of scientific data.
- Public accessibility and transparency of scientific communication.
- Using web-based tools to facilitate scientific collaboration.

These goals are matching the idea of our project, so to use an open source licence for the developed software seems to be obvious. But the licence must allow to combine the outcome of this project with closed source models, and it should be possible to distribute the combined version. In the following we explore some widely used licence with a view to this requirements:

7.1.1 Gnu General Public Licence (GPL)

The GPL is a copyleft licence, this means that derived work (e.g. modified versions of a macro-module) must also be published using the GPL. Which is, taken in isolation, not a problem. But the GPL contains also strict rules in the interaction with other components:

> “In legal practice, this arises as a common concern of clients just getting into open source. This question is usually phrased as [. . .] ‘Do I have to apply the

> GPL to my plug-in for a particular program if that program is licensed under the GPL?' [. . .] I wont keep you in suspense; the short answer is that we dont know." (Lindberg 2003)

7.1.2 Academic Free Licence (AFL)

The MASON library (see Section 7.4), which plays an important role in STROMSys, is licensed under the AFL, a permissive free software licence written by Lawrance E. Rosen, the general counsel of the Open Source Initiative (OSI). Permissive free software licences allow to use the Original Work in proprietary software, which is not in line with the open science spirit. Furthermore, the OSI's License Proliferation found it redundant with the more popular Apache Software License.

7.1.3 Open Software Licence (OSL)

The OSL is another licence written by Lawrance E. Rosen, the biggest difference to the AFL is that the OSL is a copyleft licence. But in contrast to the GPL, the OSL allows to combine the Original Work with proprietary software, the resulting product does not count as a Derived Work and therefore is not "infected" by the OSL.

Because of the near relationship to the AFL there are not any compatibility problems with the licence used by the MASON library. Thus, the OSL is used for the software developed for this project.

7.2 System Language

At present to our knowledge there is no web-based tool that facilitates the development of agent-based models (ABMs) in a collaborative manner. But many ABM platforms are written in Java (see Kravari/Bassiliades 2015) so that programs written with these platforms run without problems on any system with a Java Virtual Machine (JVM) installed.

JVM based ABM platforms can be used not only in Java but in every computer language that compiles to the JVM and allows the interoperability with Java libraries.

For the implementation of the STOEMSys modules and some additional work like the Rapid Prototyping Framework (see Section 7.6), Scala (see Odersky et al. (2004)) was chosen, which is an object-oriented, functional, statically typed programming language that fulfills the above requirement. Scala has a sophisticated type system, which made it possible to develop the Economic Types Library (see Section 7.3) and also allows, in general, to write better readable code then Java.

Scala comes with a tool called "scaladoc", which extracts (among others) a HTML documentation out of the source code. To get an optimal result, the comments should follow a special syntax. Details are described in (Scaladoc Wiki 2011).

7.3 Economic Types Library

In a programming language, types are useful because they help to avoid errors: for example, functions "know" which types they can be applied to, and if the required type does not match the type that a function is supposed to be applied to, the compiler will complain.

However, in case of numerical calculations, the types of the function parameters are often just the type DOUBLE or another fundamental numerical type. This is an error-prone approach, e.g. in the case that the modeller interchanges the parameter order accidentally, the compiler does not detect the mistake. It would be useful to tag the parameters and attributes with additional information about the value for the compiler to catch these errors.

Therefore, for STOEMSys a Scala library was developed which supports the development of economic models by providing different economic types and operators on them. Using this library, DOUBLE values can be encapsulated in instances of specialized classes with additional type parameters. Thereby the class name gives information about the kind of the value, e.g. there is a class for PRICEs and another for GOODAMOUNTs. The type parameters add further dimensions to the kind, e.g. the library allows to express the price of three dollar per kg of apples as `Price[Dollar, KG, Apples](3)`. In the current version, Euro is always used as currency and the weight dimension is ignored, which shrinks it to `Price[Apples](3)`. Similarly, five kg of apples can be expressed as `GoodAmount[KG, Apples](5)` or in short as `GoodAmount [Apples](5)`.

Taken a case class `Offer[A](p: Price[A], a: GoodAmount[A])`, two types of errors are now caught by the compiler: a) the already mentioned interchanged parameter order and b) mixing different goods, such as for example `Offer(Price[Apples](3), GoodAmount [Oranges](4))`.

Wrapping the DOUBLE values into other classes has, of course, the side effect that operators defined on DOUBLE do not work on the specific types without additional effort. This has the advantage that the operators can be limited to an economically meaningful subset. For example, the multiplication of two prices does not make any sense in economic terms. In contrast, the multiplication of an amount of a good with its price is defined in the library and will result in a new type FINANCIALAMOUNT, so that the following would compile:

```
val p = Price[Dollar, KG, Apples](3)
val a = GoodAmount[KG, Apples](4)
val m: FinancialAmount[Dollar] = p * a
```

So far, the `capital` stock consists of the GOODAMOUNTs of GENERICGOOD, GREENBUILDINGS and BROWNBUILDINGS. So it would be useful to combine these GOODAMOUNTs to a collection like an array. However, collections in the Scala standard library cannot be used without losing information about the exact type.[6] Tuples can be heterogeneous but it is not possible to iterate over tuples without losing type information again. Iterating the collection would be really useful, however, to write operators that act on those tuples, e.g. to add two bundles of goods.

The shapeless library (a type class and dependent type based generic programming library for Scala (see Sabin 2014) provides the needed heterogeneous container, called HLIST (for heterogeneous list). The type of the `capital` stock could be written as an HLIST in the following form:

[6] It would be possible to use as collection e.g. a LIST[ANY] or a LIST[GOODS] in the case that GENERICGOOD etc. inherit from GOODS but then the type of an extracted element from this list would be only GOODAMOUNT[GOODS] instead of e.g. GOODAMOUNT[GREENBUILDINGS].

`GoodAmount[GenericGood] :: GoodAmount[GreenBuildings] ::`
`GoodAmount[BrownBuildings] :: HNil`.
In STOEMSys HLISTS are created by the type constructor PERGOOD[A[_]], such that the HLIST above could be expressed as PERGOOD[GOODAMOUNT].[7]

```
type PerGood[A[_]] = A[GenericGood] ::
                     A[GreenBuildings] ::
                     A[BrownBuildings] ::
                     A[Retrofit] :: HNil
```

The HLIST also has a zip and map operation, so it is possible to write generic element-wise functions on such good bundles. But because of the heterogeneity of the mapped types, the value of the mapping function must be polymorphic. Many element-wise functions are already implemented in the library, e.g. the example of the multiplication of a PRICE with a GOODAMOUNT as given above, could be written in the same way for PERGOOD[PRICE] and PERGOOD[GOODAMOUNT]. In the case that a function that operates element-wise on a PERGOOD[_] value is missing, the following template can be used:

```
val foo: PerGood[GoodAmount]
object bar extends Poly1 {
  implicit def f[G <: Good] = at[G] { good =>
    // do something with foo.of(good)
  }
}
allGoods map bar
```

Due to construction of the `allGoods` value, the function which operates on `allGoods` is just the implicitly defined function `f` of the object `bar`. Inside this function, single elements of an HLIST that e.g. are taken from the object's closure can be extracted using the `of` method. More details about polymorphic function values can be found in documentation of the shapeless library (see Sabin 2014).

7.4 Extended MASON Framework (EMF)

A STOEMSys implementation can be created using different tools, but the most sophisticated is build around MASON, a multi-agent simulation library core, designed to be the foundation for large custom-purpose simulation on the JVM. MASON contains both a model library and an optional suite of visualization tools (Luke et al. 2005). The visualization tools are extended for STOEMSys by a dynamic display for time series, as described in the Section 7.4.1.

A model instance which is build with the EMF can be run via three different ways, which are described in the following sections:

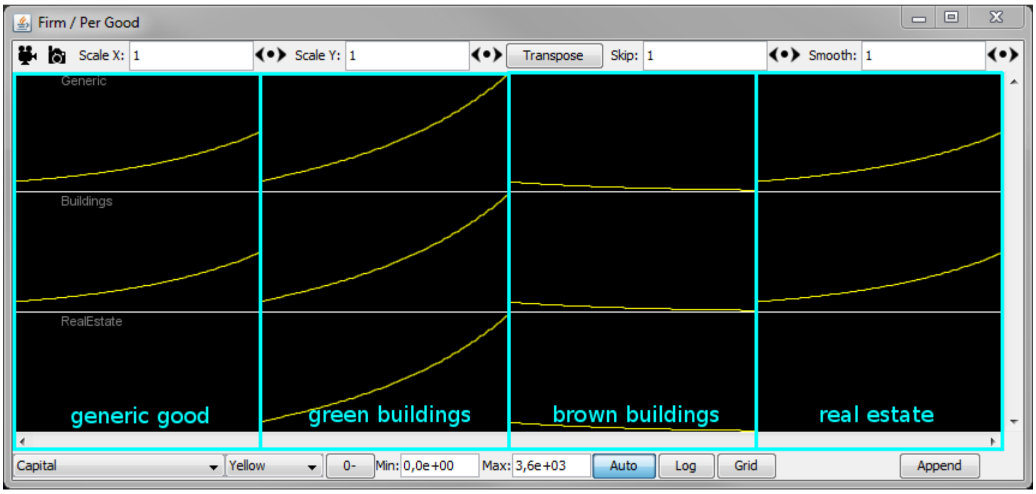
[7] That is not exactly the same type as the given example because the constructed HLIST has the additional element GOODAMOUNT[RETROFIT], which is not part of the `capital` stock. But this is not a problem as the value of this element will just always be zero.

7.4.1 MASON GUI Adapter

The first way to run a model instance is graphical user interface driven and allows an interactive exploration of model simulations. A good introduction into the user-interface is part of the MASON documentation that can be found under `http://cs.gmu.edu/~eclab/projects/mason/docs/tutorial0/index.html`. However, the display showing the results of a simulation run are not described in the above mentioned documentation, because they are not part of the MASON library itself.

An example taken from the documentation of macro-module S (see Section 8.4.2) shows the time series display mentioned above: Each row in a footer of those displays is dedicated to one variable. With the leftmost element, it is possible to change the displayed variables. Additional curves can be added with the `Append` button. The displays shows result for the different goods in different columns, but the current implementation does not show the names of the goods in the display. Figure 9 shows an example screenshot, where the goods names where added manually.

Figure 9: MASON display screenshot



7.4.2 SimEnv Interface

The second way allows to use SimEnv, a multi-run simulation environment that focuses on evaluation and usage of models with large and multi-dimensional output, mainly for quality assurance matters and scenario analysis, using sampling techniques. SimEnv provides automatisation of multi-run experiments in order to explore such relations. For more information on SimEnv see the project page: http://www.pik-potsdam.de/research/transdisciplinary-concepts-and-methods/archiv/projects/modsimenv/simenv.

In order to use SimEnv, the model has to be prepared by declaring experiment factors and model outputs in the model source code. The extended MASON modelling framework provides three Java annotations for this task:

- The annotation `@SimEnvFactor` declares a variable to be a SimEnv factor, which means SimEnv uses it as a input variable which is automatically modified.
- A special case of `@SimEnvFactor` is the annotation `@SimEnvFactorBool` that declares a variable to be a Boolean SimEnv factor.
- The annotation `@SimEnvResult` declares a variable to be a SimEnv output, which means SimEnv traces the values of this variable and uses them in postprocessing.

The results of a multi-run simulation are written into a single file using the Network Common Data Format (NetCDF). Section 7.5 describes how this file can be used for further processing or visualization.

7.4.3 Command Line Interface

An EMF model instance can be also run via a command line interface (CLI). For example, the command `java -jar macro-module-s-1.0.0.jar -Rmode -periods20-csv bau.csv` would combine the model implementation `macro-module-s-1.0.0.jar` with the configuration file `bau.csv`. The output would be written into a file called `Resultsbau.csv`.

7.5 Post-processing and Visualization

For the post-processing and visualization of the generated output by the EMF, various third party software was utilized.

7.5.1 SimEnv

Part of SimEnv is an interactive post-processor, that can be used for the results generated using the SimEnv interface. This post-prcoessor provides more than 100 filters / operators. Run ensemble related aggregated measures can be calculated by experiment-specific operators, e.g. for carry out a global sensitivity analysis of the input parameters.

7.5.2 R

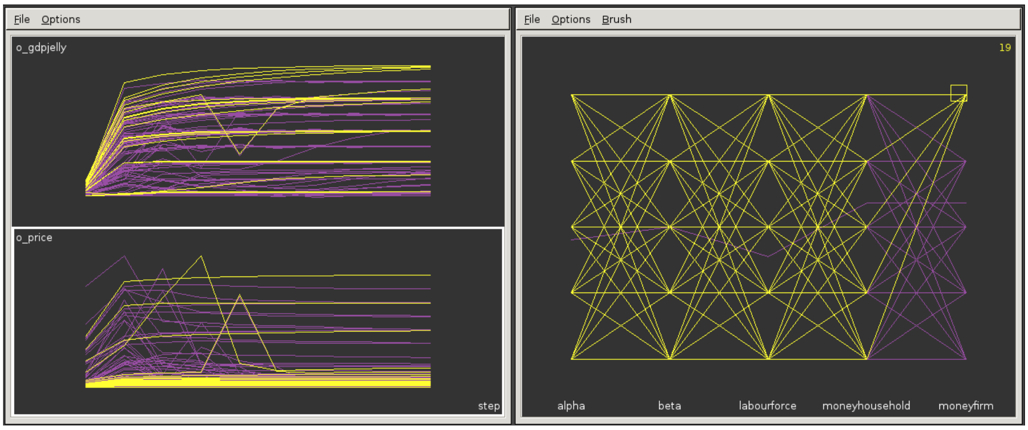
> R is a free software environment for statistical computing and graphics. [...] R provides a wide variety of statistical (linear and nonlinear modelling, classical statistical tests, time-series analysis, classification, clustering,) and graphical techniques, and is highly extensible. (The R Foundation 2015)

Part of STOEMSys is a R-script, which reads and preprocesses a script generated output file into a R-session. Several output files can be added to compare different scenarios. Also it's possible to read NetCDF files generated by the SimEnv interface.

7.5.3 GGobi

The data structures created by the R-scripts mentioned above can be transferred from R to GGobi, an highly dynamic and interactive open source visualization program for exploring high-dimensional data (see (The GGobi Foundation 2015)). Different plots of the data can be visualized simultaneous. The plots are linked together, so that runs that are marked in one plot will be highlighted in all other plots too. Figure 10 shows an example, using 3125 differnt runs of Macro-Module A (see Section 8.4.1).

Figure 10: GGobi screenshot showing the brushing feature



The left side display time-series for two different variables and 3125 runs. The right side shows the parameter combinations for those runs. Some of the runs are marked using a yellow brush.

7.6 Rapid Prototyping Framework

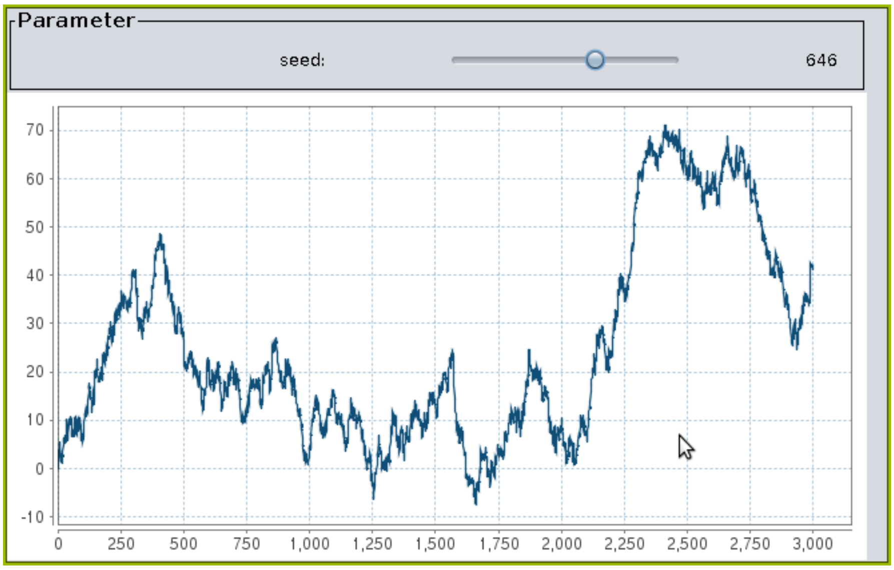
The flexibility of the Extended MASON Framework and the safety-net of the Economic Types Library described before comes with a cost, implementing new parts of a model can be sometimes cumbersome. Therefore STOEMSys provides a second, extremly small framework, which allows to explore new ideas fast and easily, but still uses Scala and therefore can integrate implementations of the Economic System Components described in Section 6.

Figure 11 shows as an example a random walk to demonstrate the user interface of the RPF. The whole code for this example is shown in the following lines:

```
object RandomWalk extends Simulation with App {
  // define parameter(s)
  val seed = Parameter("seed", stepWidth = 1, max = 1000, format = "####")
  def parameters = List(seed)
  // define chart(s)
  val walk = LineChart()
  def charts = List(walk)

  override def runSimulation() = {
    var r = new Random(seed().asInstanceOf[Int])

    val results = (1 to 3000).scanLeft(0.0){ case(acc, _) =>
                                                   acc + r.nextGaussian }

    walk.addData(results)
```

```
  }
  // open the GUI
  show()
}
```

Figure 11: Rapid Prototyping Framework example



7.7 Virtual Machine

As mentioned in Section 7.1, web-based tools would be ideal to facilitate scientific collaboration. There exist some interesting approaches, to our knowledge the most advanced is the SageMathCloud (https://cloud.sagemath.com/). But those are rather generic, tools that are more tailored to modeling and evaluating simulations, especially of agent based models, are missing in those solutions.

Installing something like the described tool chain is not an easy task, especially because not all software exist for any operating system. But a possible solution is to use the virtual machine technology. A virtual machine allows to boot a second (guest) operating system while running a different one (the host). What looks like a hard-disc for the guest OS is just a single file (called hd-image) of the host OS. Such a hd-image can contain all the system components and could be distributed via web-server, given that all components are open source.

A version control software like subversion allows to exchange the collaborative work and to update the virtual machine image.

8 STOEMSys Implementation Components

Economic concepts (Chapter 6) and computational components (Chapter 7) give content and framework for designing the specific implementations of the modelling system components which are the subject of this chapter. The first two sections briefly point out basic structural implementation concepts. Section 8.3 gives an idea about one of the basic dynamical features. These "implementation components" can be understood as "components for implementation" of STOEMSys models.

In Section 8.4, implementations of different modules are explained, Section 8.5 describes how different modules are connected, and Section 8.6 describes how data and the configuration are handled. These three elements form STOEMSys models, and can thus be considered implemented components of the modelling system.

8.1 Modular Architecture

Section 6.2 described why climate economic modelling should contain the means to model the macro-economic perspective while at the same time modelling emission-relevant sectors in detail. This implies a focus on the most important sectors in terms of CO_2 emissions and primary energy use, while not losing out of sight the macro-economic implications of measures targeted to these sectors, such as their effects on the labour market, on investors' expectations, and hence on economic growth. In order to strike the right balance between sector-specific considerations and macro-economic effects, STOEMSys uses a modular approach: it supplies a model architecture in which an agent-based macro-economic module and detailed sector-specific modules can complement each other for the assessment of costs and benefits of climate and energy policy measures.

A macro-module depicts the rest of the economy that is not modelled in detail using a specific sectoral module; macro-modules can thus be used without any further sectoral parts. The focus of this project was mainly on the development of the macro-economic part to which ideally (already existing) detailed sectoral models can be coupled.

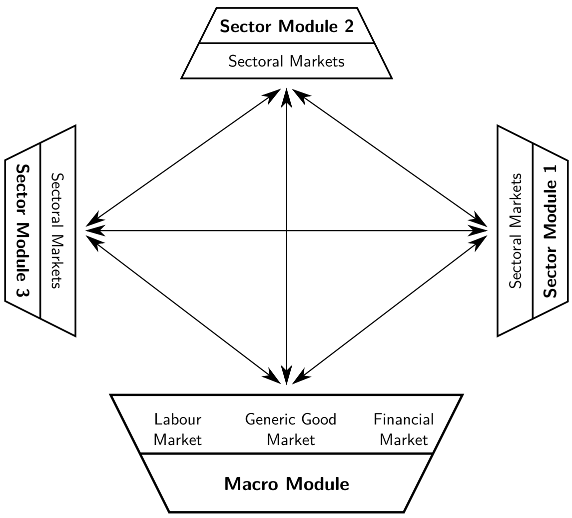
Figure 12 gives an overview of the modular structure. Each module also contains one or more markets. For sectoral modules these are the markets for the goods produced within this sector. The macro-module contains labour and financial markets as well as a market for the "generic good" (also "jelly") which represents all the goods not produced in a sectoral module.

Different modules interact at the markets. For each market (sectoral or part of the macro-module), information from all other modules is needed to determine the aggregate demand, and information about the price and the actual amount of the good traded has to be sent to all other modules.

8.2 Aggregate Agents

The STOEMSys module development draws on previous work with multi-agent models (see, e.g. Mandel et al. 2009; Wolf et al. 2013b) where the number of agents was typically between

Figure 12: Modular Architecture



100 and 10000. For such models, types of agents are implemented on a computer, and then many copies of each type of agent are initialised using data generated according to given probability distributions. While this is probably what one expects when hearing of an agent-based model, STOEMSys modules do not use this technique, at least not yet. It is possible to extend the modules presented in Sections 8.4.1 and 8.4.2 to incorporate many agents of the same kinds, but for now, these modules contain aggregate agents.

These aggregate agents stem from the module development taking into account the insights from aggregate models of production described in Section 6.1.1. Single agents were made explicit in an aggregate model of production by specifying which steps are undertaken by which agents (e.g. labour in a production function is supplied by households). This also meant specifying how agents make their decisions and how market outcomes are established in the interaction between agents who might have different desires. The "next step" of introducing many copies of certain kinds of agents (firms and households, but not, e.g., central banks) was not deemed useful so far. The fact that agents are aggregate is, however, taken into account in the module design. For example, the generic firm in the macromodules described below (again, Sections 8.4.1 and 8.4.2), does not maximize profit, but "optimizes" its profit to zero, to represent an average competitive market of many firms.

A reason for pointing out the aggregate nature of modelled agents is to underline the difference from what is known as "representative agents" used in many economic models: all agents are assumed to have the same preferences and therefore they can be replaced by a single individual. In particular, such representative agents are mostly considered to have perfect foresight and to be perfectly rational, which is not the case for STOEMSys agents, as described in Section 6.4.1.

8.3 Price Dynamics Through Expectations and Learning

One central question in non-equilibrium economic modelling is how prices are set and how they adjust over time. This section describes a mechanism for price development through expectations and learning that is implemented in STOEMSys.

This price dynamics is determined by the behaviour of the firms in the market. We assume that the main objective of every firm is to maximize its profit, but in the situation of perfect competition, for an aggregate firm this means that the optimal aggregate extra-profit (i.e. the difference of revenues and labour and capital costs) is zero (see, e.g., von Neumann 1945). The outcome of this optimization in combination with the firm's demand expectations determines the price of the good. Price development depends on different assumptions of the (aggregate) firm concerning the demand for its good, on assumptions about the costs, as well as on the adjustment process for the expected demand.

8.3.1 The Firm's Price Adjustment

In the simplest setting we have two aggregate agents, one firm producing goods and one household as a consumer. The firm produces the generic good at its optimal profit and sells it for the respective price (depending on the expected aggregate demand curve). The firm does not know the exact demand curve. It only knows the consumer's demand for the good for prices it has set in the past. At each time step, it uses this information to improve its expectations for the demand curve.

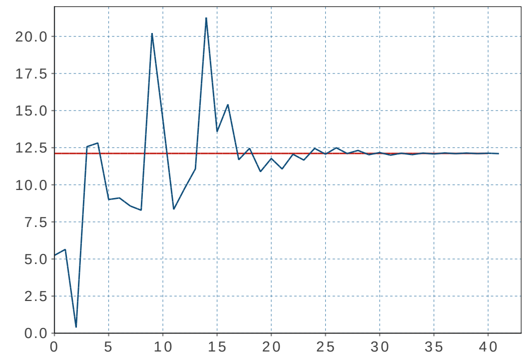
The actual demand curve of the household most likely differs from the one expected by the firm. The usual approach is to derive the demand curve from a maximization of the household's utility. The demand curve can be different at every time step since important factors in this maximization problem may change over time, e.g. the household's income which may depend upon the firm's production and profit. To test the price development algorithm without this kind of feedback, the firm's learning algorithm was first applied to a situation where the household's demand curve does not depend on the firm's performance and is constant over time.

The test setup can be described as follows:

- There is a constant *real demand curve* which describes the relation between prices and the quantities demanded by the consumers.
- The firm has an idea about what the real demand curve may look like, i.e. it has an *expected demand curve*.
- The firm decides how much of the generic good to offer at which price by optimizing its expected profit. The expected profit is derived from the expected demand curve and the (expected) costs.
- The firm's offer may be different from the household's demand. The firm offers a quantity q_S at a certain price p and learns about the demand q_D at price p. The firm uses this information to improve its expected demand function.

Figure 13 shows typical simulation results for the price development over time. At each time step, the firm receives new information about the real demand curve and improves its expected demand curve. After about 30 time steps, the firm's expectations about the demand match the real demand and therefore the price set by the firm equals the "real" price, i.e. the price that is obtained if the firm has total information about the household's demand (red line).

Figure 13: Price Adjustment by Learning



The firm's price adjustment by learning over time for the case of a constant demand curve (corresponding to the price indicated by the red line)

8.3.2 Integration into STOEMSys

The firm's learning algorithm described in the previous section has been implemented into STOEMSys. Firms can chose to plan their production using the profit optimization as described above and set the price of the good accordingly. The household is price-taker and only decides how much to consume at the price set by the firm. Figure 14 sketches how firm and household act on the goods market. At each time period, the following steps are taken:

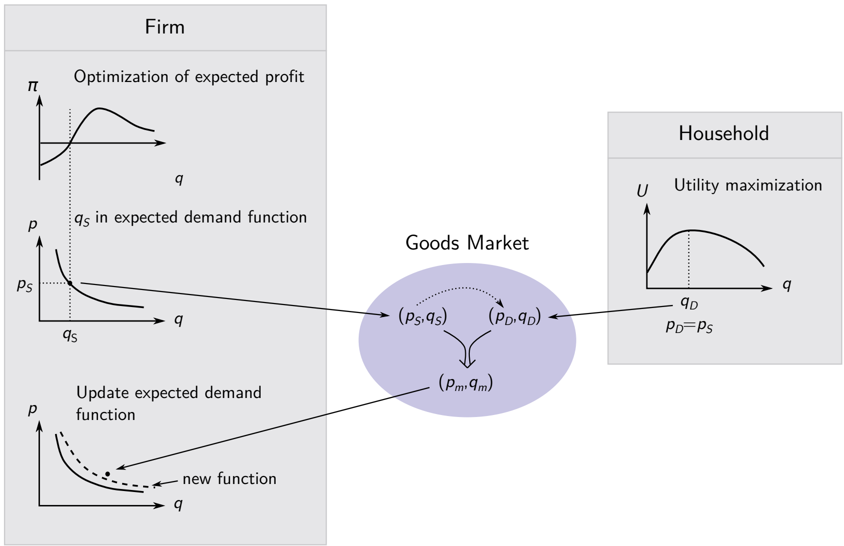
1. *Firm decides supply*: The firm has expectations about the household's demand. By optimizing its expected profit it decides how much to produce (q_S) and sets the price p_S for the goods.

2. *Household decides demand*: The household is a price-taker ($p_D = p_S$). It decides how much of the goods to demand (q_D).

3. *Goods transaction*: The quantity q_M sold and bought on the goods market is determined (e.g. by taking the minimum of q_S, q_D). The market price is the price set by the firm ($q_M = q_S$).

4. *Expectations update*: Using the transaction information (q_M, p_M) or the information about the demand (q_D, $p_D = p_S$) the firm updates its expected demand function. A detailed description of how the update of expectations is done can be found in the sections describing the different implementations of the system's instances (see e.g. Section 8.4.1.2 or 10.3.2).

Figure 14: Price Dynamics on the Goods Market



Scheme of price dynamics by profit optimization (for description see text)

8.4 Modules

So far, two different macro-modules have been designed. Taking into account the complementarity of modelling the basic dynamical features in a analytically understandable way and simulating a given economic system (see section 4.2) one of the macro-modules is designed to aim at problem analysis (Section 8.4.1) and the other at policy simulations (Section 8.4.2). To show the interactions of a macro-module with a sectoral module, a simplified buildings module has been developed as well (Section 8.4.3).

8.4.1 Macro-Module A: Macro-Module for Problem Analysis

Macro-Module A is designed to gain insight into the macro-economic principles of a non-equilibrium system. For the sake of simplicity and clarity, sophisticated features for calibrating the system have not been implemented. This allows for a straightforward mathematical description and concentration on the main dynamical principles.

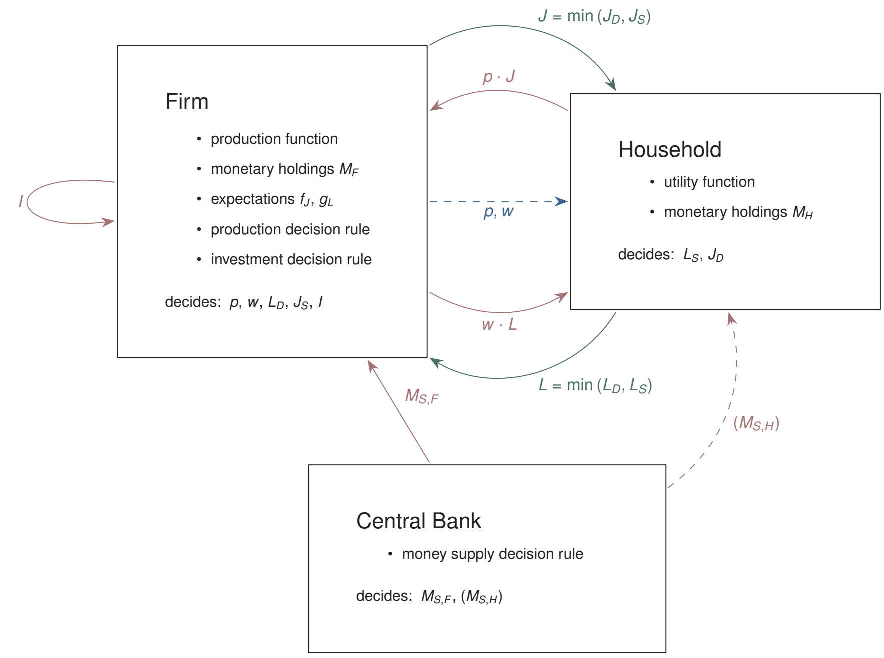
8.4.1.1 Overview of MM-A

The MM-A consists of a firm that produces jelly using capital and labour, a household that consumes jelly and provides labour, and a central bank that can change the money supply. Figure 15 gives an overview.

Important feature of the MM-A agents are:

- **Firm** The firm is an aggregate. Assuming perfect competition on the jelly market, optimally the firm sells its goods at a price at which revenues equal production costs. In

Figure 15: Overview of MM-A



Overview of macro-module A: the three (aggregate) agents and their interactions.

MM-A, the firm does not know exactly what will be revenues and cost but has expectations about the jelly demand and about the labour supply of the household. How these expectations are used to determine the jelly price is described in detail in section 8.3; the same routine is used for the firm to update its expectations about labour supply (amount of labour offered depending on wage). Thus the firm optimizes its profit depending on its expectations, sets jelly price and wage, and learns about actual jelly demand and labour supply using this information to update its expectations. The firm decides how much of its production to invest taking into account past GDP (or output) growth rates and its (fixed) capital growth target.

- **Household** The aggregate household maximizes its utility which is represented by a labour supply and a jelly demand function. The jelly demand depends on the household's monetary holdings. At the current state of the module, the household does not decide about what part of its income to save. For now, savings of the household consist of the value of the firm that it owns.

- **Central Bank** The central bank in MM-A increases the amount of money in the system. Different rules can be applied, e.g. the bank can finance the firm's investment or it can increase the money supply aiming at a fixed inflation target (see Section 9.2 for details). Usually the money supply is increased giving extra money to the firm but also an increase on the household's side can be modelled.

8.4.1.2 The Dynamic System

MM-A is still a very aggregate model of the economy with only three agents of which especially household and central bank are still very simplified. However, even that reduced a system can already exhibit quite complex dynamics. The following equations describe MM-A as a dynamical system (state variables are marked in red). For an overview of the variables (and superscripts) see Table 1.

Table 1: MM-A Variables

g	growth
I	investment
L	labour
q	jelly amount
p	jelly price
w	wage
C	consumption
(κ, θ)	parameters of expected jelly demand function
(z, ξ)	parameters of expected labour supply function
d	dividend
m	money
η	productivity
K	capital

with superscripts:

S	-	supply
D	-	demand
M	-	market
P	-	planned
R	-	realized
F	-	firm
H	-	household

$$I_{t+1}^{(P)} = (\gamma \cdot \tilde{g} + (1-\gamma) \cdot g_t + \delta) \cdot K_t \quad \text{with} \quad 0 \leq \gamma \leq 1 \tag{1}$$

$$L_{t+1}^{(D)} = \arg\min_L |(\rho(L) - I_{t+1}^{(P)}) \frac{\kappa_t}{\rho(L)^{\theta_t}} - \omega_t^{(e)}(L) \cdot L - p_t^{(M)} \cdot K_t \cdot d_t| \tag{2}$$

$$\text{with} \quad 0 \leq L \leq \arg\min_{L \geq 0} |\omega_t^{(e)}(L) - \frac{m_t^{(F)} - p_t^{(M)} \cdot K_t \cdot d_t}{L}| \tag{3}$$

$$\text{and} \quad \rho(L) = K_t^{\alpha} \cdot (\eta_t \cdot L)^{1-\alpha} \tag{4}$$

$$\text{and} \quad \omega_t^{(e)}(L) = \max\{w_{\min}, \left(\frac{z_t}{L_f - L}\right)^{\frac{1}{\xi_t}}\} \tag{5}$$

$$q_{t+1}^{(P)} = K_t^{\alpha} \cdot (\eta_t \cdot L_{t+1}^{(D)})^{1-\alpha} \tag{6}$$

$$p_{t+1} = \frac{\kappa_t}{(q_{t+1}^{(P)})^{\theta_t}} \tag{7}$$

$$w_{t+1} = \max\{w_{\min}, \left(\frac{z_t}{L_f - L_{t+1}^{(D)}}\right)^{\frac{1}{\xi_t}}\} \tag{8}$$

$$L_{t+1}^{(S)} = L_f \left(1 - \sqrt{\frac{w_{\min}}{w_{t+1}}}\right) \tag{9}$$

$$L_{t+1}^{(M)} = \min\{L_{t+1}^{(D)}, L_{t+1}^{(S)}\} \tag{10}$$

$$q_{t+1}^{(S)} = K_t^{\alpha} \cdot (\eta_t \cdot L_{t+1}^{(M)})^{1-\alpha} \tag{11}$$

$$C_{t+1}^{(P)} = \frac{m_t^{(H)}}{p_{t+1}} \tag{12}$$

$$q_{t+1}^{(D)} = C_{t+1}^{(P)} + I_{t+1}^{(P)} \tag{13}$$

$$I_{t+1}^{(R)} = \min\{I_{t+1}^{(P)}, q_{t+1}^{(S)}\} \tag{14}$$

$$C_{t+1}^{(R)} = \min\{C_{t+1}^{(P)}, q_{t+1}^{(S)} - I_{t+1}^{(R)}\} \tag{15}$$

$$q_{t+1}^{(M)} = I_{t+1}^{(R)} + C_{t+1}^{(R)} \tag{16}$$

$$g_{t+1} = \frac{q_{t+1}^{(M)} p_{t+1} - q_t^{(M)} p_t}{q_t^{(M)} p_t} \tag{17}$$

$$(\kappa_{t+1}, \theta_{t+1}) = \arg\min_{\kappa,\theta} \left(\sqrt{\frac{\ln^2 \Delta_{t+1}^{(q)} + \phi \cdot \ln^2 \Delta_t^{(q)}}{1+\phi}} + \psi \sqrt{\ln^2 \frac{\kappa}{\kappa_t} + \ln^2 \frac{\theta}{\theta_t}} \right) \tag{18}$$

$$\text{with } \Delta_{t+1}^{(q)} = \frac{q_{t+1}^{(D)} \cdot g_{t+1}}{(\kappa/p_{t+1})^{\theta}}, \quad \Delta_t^{(q)} = \frac{q_t^{(D)} \cdot g_{t+1} \cdot g_t}{(\kappa/p_t)^{\theta}} \tag{19}$$

$$\text{and } \kappa > 0, \ 1 > \theta > 0 \tag{20}$$

$$(z_{t+1}, \xi_{t+1}) = \arg\min_{z,\xi} \left(\sqrt{\frac{\ln^2 \Delta_{t+1}^{(L)} + \phi \cdot \ln^2 \Delta_t^{(L)}}{1+\phi}} + \psi \sqrt{\ln^2 \frac{z}{z_t} + \ln^2 \frac{\xi}{\xi_t}} \right) \tag{21}$$

$$\text{with } \Delta_{\tau}^{(L)} = \frac{L_{\tau}^{(S)}}{L_f - z/w_{\tau}^{\xi}} \tag{22}$$

$$\text{and } z > 0, \ \xi > 0 \tag{23}$$

$$d_{t+1} = \min\{d_{\text{target}}, \frac{0.99 \cdot m_t^{(F)} + (q_{t+1}^{(M)} - I_{t+1}^{(R)})p_{t+1} - L_{t+1}^{(M)} w_{t+1}}{p_t^{(M)} K_t}\} \tag{24}$$

$$m_{t+1}^{(H)} = m_t^{(H)} + w_{t+1} \cdot L_{t+1}^{(M)} + p_t \cdot K_t \cdot d_{t+1} - p_{t+1} \cdot C_{t+1}^{(R)} + X_t \tag{25}$$

$$m_{t+1}^{(F)} = m_t^{(F)} + p_{t+1} \cdot (q_{t+1}^{(M)} - I_{t+1}^{(R)}) - w_{t+1} \cdot L_{t+1}^{(M)} - p_t \cdot K_t \cdot d_{t+1} + Y_t \tag{26}$$

$$\eta_{t+1} = \eta_t \cdot \left(1 + \frac{I_{t+1}^{(R)} - \delta \cdot K_t}{K_t}\right) \tag{27}$$

$$K_{t+1} = K_t(1-\delta) + I_{t+1}^{(R)} \tag{28}$$

Here, X_t and Y_t in equations (25) and (26) are the terms that describe money supply by the central bank. For different versions of X_t and Y_t see Section 9.2.

8.4.2 Macro-Module S: Macro-Module for Policy Simulations

Macro-module S (MM-S) is similar to MM-A in many ways: it has the same agents, and also many of the dynamic equations are the same or very similar. However, there are some basic differences. While MM-A is designed for problem analysis by understanding basic principles leaving out everything not necessary for this task, MM-S is designed for simulating different climate policies. It is calibrated on the basis of real data and is has an interface for sectoral modules to be coupled to it.

As for MM-A, the firm has to take two decisions, one about how much to produce and one about how much to invest. In contrast to MM-A, MM-S provides a variety of different decision functions for these two tasks. Box 1 gives an overview.

Box 1: Firm's Decision Functions

Within one time step, the firm has to make two decisions: it has to determine the amount of production and it has to decide how much it wants to increase its capital stock.

Production Decision

The firm's production planning is modelled choosing one of four implemented production planning functions:

- *Profit Optimization*: The firm optimizes expected profits taking into account its expectations about the demand. Principles are explained in section 8.3.
- *GDP Growth*: The firm plans to increase its production by a rate that equals the latest observed GDP growth rate.
- *Capital Growth*: The firm plans to increase its production by a rate that equals the latest capital growth rate.
- *Fixed Growth*: The firm always plans to increase its production by a fixed growth rate.

Investment Decision

For the firm's investment decision, one of three implemented investment planning functions can be chosen:

- *GDP Growth*: The firm plans to increase its capital stock by a rate that equals the latest observed GDP growth rate.
- *Capital Growth*: The firm plans to increase its capital stock by a rate that equals the latest capital growth rate.
- *Output Growth*: The firm plans to increase its capital stock by a rate that equals the latest observed output growth rate.

A very detailed description of the implementation of MM-S together with a simple sectoral buildings module is given in Chapter 10. The dynamic equations of MM-S can be found in Section 10.3. The calibration procedure is described in Chapter 11. In a nutshell, the agents in MM-S behave as follows:

- **Generic Firm**
  Labour demand: The firm's labour demand is determined by its desired production; for production planning, one of the functions listed in Box 1 is chosen.

Price and wage: Good price and labour wage are set by the firm according to production planning and the firm's expectations about the household's demand for generic good and labour supply.
Investment: The firm's demand for investment goods (generic good and where applicable sectoral goods) is determined by its actual investment decision function as given by one of the functions listed in Box 1.
Expectation update: The firm updates its expectations about the demand for its good by learning from the actual demand on the market as described in Section 8.3.

- **Household**
  Labour supply: The household supplies labour according to the labour demand of all firms up to a maximum amount.
  Income: The household's income is the sum of its labour and capital imcome, i.e.

$$Y_t = \sum_{g \in \{\text{firms}\}} w(L^{(D)}_{g,t}) \cdot L_{g,t} + \sum_{g \in \{\text{firms}\}} r \cdot p_{g,t-1} \cdot K_{g,t-1}. \tag{29}$$

  Disposable Income:

$$\begin{aligned} Y_t^{\text{disp}} &= \begin{cases} d & \text{if } d \geq Y_{t-1}^{\text{disp}} \\ d + \min\left(Y_{t-1}^{\text{disp}} - d, M_{t-1}^{(H)}\right) & \text{else} \end{cases} \\ \text{where} \quad & d = (1-s) \cdot Y_{t-1} \\ & \text{with } 0 \leq s \leq 1 \text{ being the fraction of its income to be saved.} \end{aligned} \tag{30}$$

  Demand for (sectoral) goods / consumption: The disposable income of the household is spent for consumption. If the household consumes not only the generic good but also sectoral goods, distribution rules are defined.

- **Central Bank**
  Implicitly, a “central bank” is present as a source of money, as the firm can spend more than its current monetary holdings.

8.4.3 Simplified Sectoral Buildings Module

In order to show the interactions of a macro-module with a sectoral module, a simple sectoral buildings module has been implemented. It consists of two sectoral firms, construction firm and retrofit firm, that produce two respective goods, new buildings and retrofit. For the simulation of the buildings stock, buildings have been divided into two classes, green buildings and brown buildings; the only difference between the two classes is the amount of emissions they produce. All new buildings built by the construction firm are green buildings. Retrofitting turns brown buildings into green buildings. For replacement investments into buildings, retrofit is needed as well.

- **Retrofit Firm**
  Labour demand: The planned production of “retrofit" is the sum of the retrofit demand of all agents. The labour demand of the retrofit firm is the amount of labour needed for

its planned production.
Price for retrofit: For simplicity,[8] the price for retrofit is set to 1.
Investment: The firm's demand for investment goods (generic good and buildings) is determined by its actual investment decision function (as given by one of the functions listed in Box 1) which determines a planned investment rate i_t. That means for the demand of generic good

$$G_t^{(D)} = (i_t + \delta_K) \cdot K_{t-1} \tag{31}$$

and for the demand for new buildings (construction)

$$C_t^{(D)} = i_t \cdot (B_{t-1}^{\text{green}} + B_{t-1}^{\text{brown}}). \tag{32}$$

Retrofit demand: The demand for retrofit is given by the rate ϵ with which the firm desires to retrofit its buildings stock plus the replacement investments, i.e.

$$R_t^{(D)} = \epsilon \cdot B_{t-1}^{\text{brown}} + \delta_B \cdot (B_{t-1}^{\text{green}} + B_{t-1}^{\text{green}}). \tag{33}$$

- **Construction Firm**
  Labour demand: The firm's labour demand is determined by its desired production; for production planning, one of the functions listed in Box 1 is chosen.
  Price for construction: For simplicity,[9] the price for green buildings is set to 1.
  Investment: The firm's demand for investment goods (generic good and buildings) is determined by its actual investment decision function (as given by one of the functions listed in Box 1) which determines a planned investment rate i_t. That means for the demand of generic good

$$G_t^{(D)} = (i_t + \delta_K) \cdot K_{t-1} \tag{34}$$

and for the demand for new buildings (construction)

$$C_t^{(D)} = i_t \cdot (B_{t-1}^{\text{green}} + B_{t-1}^{\text{brown}}) \tag{35}$$

Retrofit demand: The demand for retrofit is given by the rate ϵ with which the firm desires to retrofit its buildings stock plus the replacement investments, i.e.

$$R_t^{(D)} = \epsilon \cdot B_{t-1}^{\text{brown}} + \delta_B \cdot (B_{t-1}^{\text{green}} + B_{t-1}^{\text{green}}). \tag{36}$$

MM-S and the simple buildings module have been combined. Section 10 documents the resulting model, for an overview, see Figure 31 therein.

[8] Upon initialisation, all prices are 1, meaning that the units of goods are stated in "the amount of the good that costs 1 at the initialisation date". This choice is common for economic models, given that there is no natural unit for comparing different goods as, say, buildings and apples anyhow. The fact that the price stays at 1 means that there are no price dynamics for the sectoral firms. As the module is meant to be replaced by a detailed sectoral module, this approximation seemed good enough for the "dummy" buildings module.

[9] See retrofit price.

8.5 Sectoral Module Interface

This section provides a guideline for extending MM-S with additional sector-specific modules, hence providing the interface from the macro-module to these. This requires some understanding about the basics of the implementation, an overview is given in Section 8.5.1, before the remaining sections lay out the necessary steps for adding a new sectoral module. This is demonstrated using the transport sector as an example, without taking any specific features of this sector into account. The result of these steps is a model with a finer sectoral granularity, that allows to add specific properties of the new sector afterwards.

The main target audience of this section are modellers. Thus it is assumed in the following that the reader can interpret UML diagrams and is familiar with the jargon of software developers. As the economic type system, presented in Section 7.3, is an important element of the implementation, it is useful to read that section before this one.

8.5.1 Implementation Overview

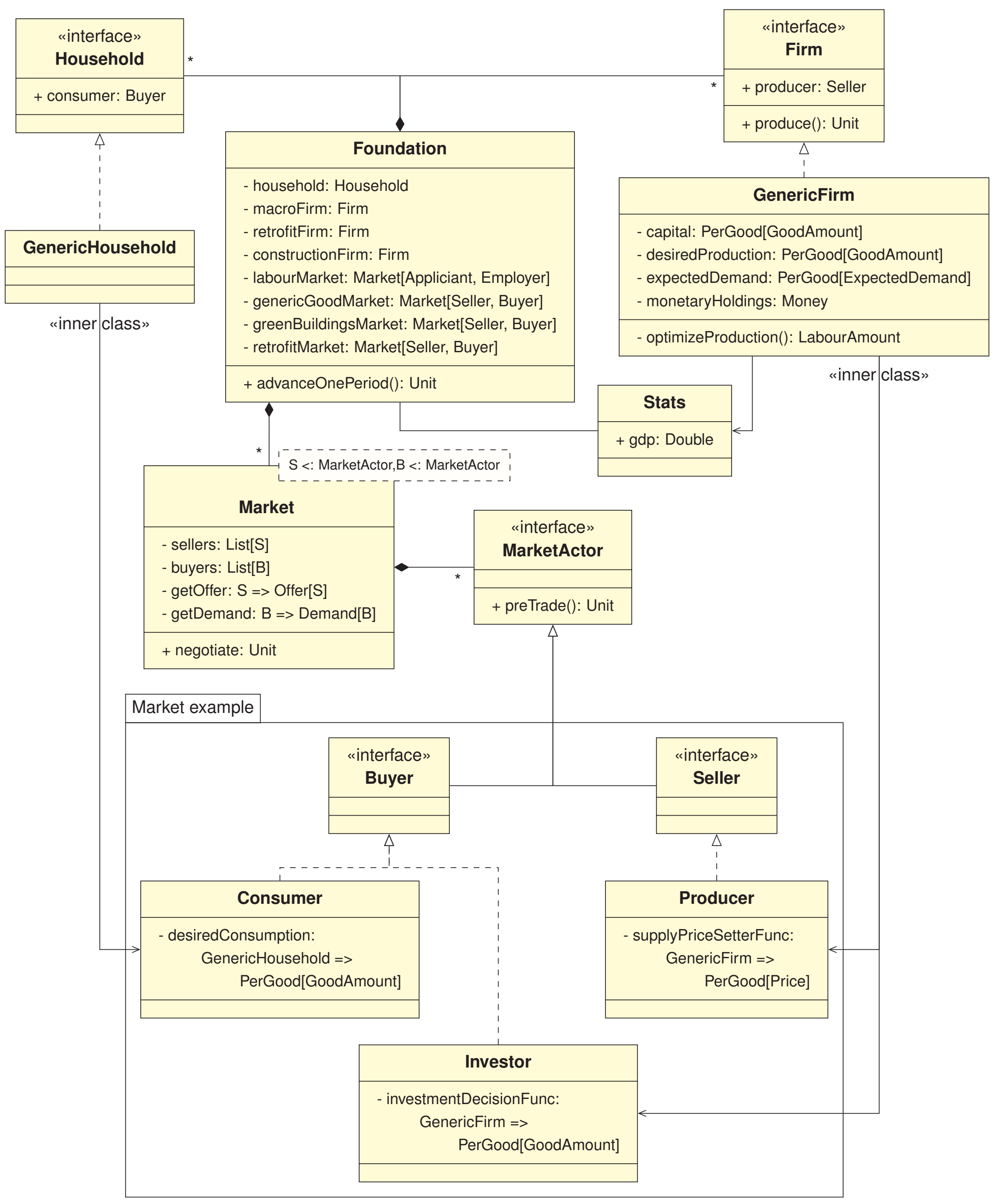
Figure 16 gives an overview of the main structure of the MM-S coupled with buildings module. It shows a single market as an example how markets are implemented and only a selection of the attributes and methods that should give an idea about the spirit of the classes or traits.

The "root" of the implementation, that constructs all the agents and other entities of the model, is the class FOUNDATION. A single instance of this class is created by the MASON framework, and this instance is also the interface between MASON and the model itself. E.g. the function `advanceOnePeriod` of this interface is called from MASON to trigger the calculations of a single period. The results can then be collected via instances of so called PROBEs, which are not part of this description.

The FOUNDATION instance constructs all agents which are, in the current implementation, one households and three firms. The concrete implementations of the household and firms, e.g. the GENERICHOUSEHOLD and the GENERICFIRM, inherit from the simple traits HOUSEHOLD or FIRM, which are also acting as an interface between the FOUNDATION and the agents. The traits mainly define the different roles that agents play on the different markets, e.g. a household is always a consumer of goods, and it acts as a CONSUMER on the generic good market. Another possible role, not shown in the diagram, would be the household as an actor who retrofits brown buildings, this role is called RETROFITORDERER in the implementation (see also Section 10.3.5 for more detail about the roles of the agents in the different markets).

Also the labour market and the three different goods markets are constructed by the FOUNDATION. The different MARKETs are not specialized via inheritance but via MARKET constructor parameters in combination with type parameters for the MARKET. The former configure the market to the different needs, while the latter determine the types of its buyers and sellers. The most important constructor parameters are one list each of sellers and buyers, a function that gives the current offer for a seller (the overall offer in this period minus the amount already sold) and respectively a function that gives the current demand for a buyer. When a negotiation method is called, the MARKET first calls `preTrade` for each MARKETACTOR. For example, in the `preTrade` implementation of a PRODUCER, a GENERICFIRM calculates the price of its demand, using the `supplyPriceSetterFunction`. Then the MARKET matches the buyers and

Figure 16: UML diagram showing the main structure



sellers, the details of this process depend on the concrete negotiation method implemented. Currently, only one method is implemented, called `negotiateFirstComeFirstServed`, the details for this method are described in Section 10.3.5.

The agents and also the markets do not have a reference to the FOUNDATION instance, to improve the overall modularity. Information about the "world" is given from the FOUNDATION to the agents via separate classes, e.g., the information about GDP, which the firms need for some decision functions, is given via the STATS class.

8.5.2 Add a New Type

It is likely that an additional sector-specific module will introduce a new kind of good. In our model case, the transport sector has a single good, called transportation.

The goods are defined in the MODELTYPES object as classes that inherit from the class GOOD. These classes do not have any attribute or methods implemented, they are just used as tags, so that the compiler can distinguish between the different goods. In the same spirit, an implicit value for each of the goods is defined. So `class Transportation() extends Good` and `implicit val transportation = new Transportation()` would introduce the product of the transport sector as the type TRANSPORTATION to the model.

Most of the time, this new type should be also part of the PERGOOD[A[_]] type constructor, explained in 7.3. Dual to this type constructor, there exists an HLIST of all the implicit values called allGoods. So this list would be extended to

```
val allGoods = genericGood ::
               greenBuildings ::
               brownBuildings ::
               retrofit ::
               transportation :: HNil
```

As shown in Section 7.3 above, this value can be used to iterate over all the different goods. And from a good bundle value like `capital`, the value of a single good can be extracted using the `of` method which is implemented in an implicit class for the `PerGood[GoodAmount]` type. In the current implementation, this method relies on pattern matching, and a new case must be added for each new good. This is also necessary for the implicit classes of PERGOOD[LABOURAMOUNT], PERGOOD[DEPRECIATION], PERGOOD[PRICE] and for PERGOOD[RATE].

8.5.3 Add a New Firm

The newly introduced good TRANSPORTATION is not produced by any of the existing firms. Theoretically, a firm in the modelling framework can produce multiple goods, so it would be possible to change the parameters of an existing firm so that this firm will also produce TRANSPORTATION. However, it is more likely that together with a new good also a new firm is part of the sectoral extension.

Therefore, in our showcase a new value called `shippingFirm` is declared in the FOUNDATION constructor `var shippingFirm: Firm = _`. In the case that the existing implementation of the generic firm is flexible enough to represent the firm's behaviour with its own parameter set, this can be done by adding the line `shippingFirm = new GenericFirm(shippingFirmInitValues, stats, "Shipping firm")` to the `initModel` method of FOUNDATION, where the parameter `shippingFirmInitValues` is an instance of GENERICFIRMINITVALUES. Otherwise a new class must be written, that implements the FIRM trait.

8.5.4 Change Market Structure

Two modifications of the market structure are necessary, the new firm must be added as an actor to the existing markets and a new market must be created for the introduced good.

The market structure is also defined in the `initModel` method of the FOUNDATION. The market actors are parameters of the market constructor, which contains a list of all buyers, and a list of all sellers. So the buyers list of each market must be extended with the new firm.

To construct a new good market, the `buildMarket` function of the GOODMARKET object can be used, which needs only those lists of sellers or buyers and takes care of the remaining market configuration. So in our example, in the market for the TRANSPORTATION good, the following lines would be added:

```
transportationMarket = GoodMarket.buildMarket[Transportation](
  List(shippingFirm.producer),
  List(firmGeneric.investor,
       constructionFirm.investor,
       retrofitFirm.investor,
       shippingFirm.investor,
       household.consumer))
```

8.5.5 Modify the Production Functions

The existing production functions of the firms do not utilize the introduced good. As described in Section 10.3.6, the firms use Cobb-Douglas production functions, with one factor each for labour, generic good and other sectoral goods (e.g. buildings). An alternative production function exists, which only utilizes labour and the generic good. Which production function is used by a firm depends on the simulation configuration.

In the case that every firm needs the new good, it is sufficient to extend the `allSectors` CAPITALPRODUCTIONFACTORFUNction of the GENERICFIRM object. If some firm does not utilize this good, the current `allSectors` should be copied and renamed, and also added to the list of CAPITALPRODUCTIONFACTORFUNctions in the FIRMINITVALUES object.

8.5.6 Modify the Data File

To finish the introduction of a new sector specific module, the data file must be changed according to the model structure changes described above. Reading and writing data files is handled by the MASON extension, which uses reflection to introspect classes that inherit from INITVALUESBASE. Therefore, the following changes must take place to add the transport sector example:

- Add a new variable `capitalTransportation` to the FIRMINITVALUES class.
- Also in FIRMINITVALUES, enhance the capital method, so that the returned capital bundle also incl. `capitalTransportation`.

- Add a depreciation rate for the transportation good to the COMMONINITVALUE class.
- As for the capital, also the depreciation method must be enhanced by the new depreciation rate.
- Create a new class `ShippingFirmInitValues` which inherit from `FirmInitValues`. Beside the concretion of the abstract attributes and methods of `FirmInitValues` the new attribute `productionTransportation` must be added to this class.
- The implementation `production` method of the `ShippingFirmInitValues` must be `zeroGoodAmount.updatedElem(GoodAmount[Transportation] (productionTransportation))`.

8.6 Data- and Configuration Files

Consisting of several modules that are geared to policy simulation, STOEMSys needs to flexibly accept input data in order to initialize each model for the question under study. In terms of economic data, this may mean providing initial data for different moments in time, for different regions, or for different levels of aggregation in the represented economic system.

As described above, modules may have several mechanisms implemented for decision rules of agents. The user needs to be able to flexibly choose the configuration for the simulations intended.

8.6.1 The Default Data File

To provide the flexibility of initializing the module so that it can represent any given economic system at a certain point in time, STOEMSys modules for simulation come with a so-called default data file. This file is integrated into the model code, so that STOEMSys models can also be used in stand-alone-mode.

When opening the graphical user interface, the default data are displayed according to modules, agents, etc. The model user can set the conditions for simulation runs by making changes to single data entries within the GUI, simply by changing values and saving.

For more substantial changes, the entire set of default data can be extracted from the code and saved to a commonly used data-file format, comma-separated values (.csv). This is a plain text file that uses commas (and line endings) as a separator between the different entities. The whole data file can be interpreted as a table where the number of rows is equal to the number of lines of the file, and the number of columns is equals to max(1 + number of commas in row). In fact, the file can be opened and manipulated using standard spreadsheet analysis programmes. Entries in the table can be comments, which supply information to the model user but are ignored by the programme itself, information about variable values, for example, their names or (economic) types, or the thus described variable values. The latter correspond to the values that the model user can also change “by hand” in the GUI. Section 11.2.2 provides the documentation of an exemplary default data file for a model consisting of MM-S combined with the buildings module.

8.7 Documentation

As pointed out in Section 4.3, providing open-source models is a necessary but by no means sufficient condition for transparency in scientific exchange about the analysis of costs and benefits of climate policy.

The issue of documentation is therefore taken seriously in STOEMSys, making it an explicit component of the system. Documentation of the code itself, within the code, has been treated briefly in Section 7.2. An accessible documentation at this level is important, especially for other modellers who might want to use and extend the code in open-source mode.

Beyond that, however, STOEMSys work has reiterated the challenges, rather than providing a single solution. The work on complex agent-based models has pointed out yet again the necessity of different types of documentation for different purposes or uses. A mix of equations, images, natural language text descriptions, pieces of code, and simulation results plotted has proved useful and necessary even for the communication within the group of researchers working on the different modules of STOEMSys.

Having used the Dahlem ABM documentation guidelines (Wolf et al. 2013a) at three points throughout the development of a model, from simple to more complex, it seems that the "overview"- and "design concepts"- sections of these guidelines are less useful than what was hoped for. Many of the questions focus on aspects that did not apply to the models that needed to be documented, while important elements of STOEMSys modules were difficult to flag within the structure of these sections. The "functional specification"-section (Section 10.3) while not easy to complete, proved to be more relevant to our case: it forces the modeller to describe the model to a large degree of detail. Often, this degree of detail is not reached for more complex computational models, as modellers refrain from publishing "all the equations" or similar. It is useful for anyone wanting to know the details of the model, and thus in particular for modellers who might want to interact with STOEMSys modellers to jointly integrate models. Modellers who might want to extend STOEMSys models in open-source mode, would rather need even more detail, in particular about the implementation. This led to descriptions of the type presented in Section 8.5.

Complementary to the documentation at this level of detail, however, more distilled documentation is needed for giving an overview to those who do not have the time (or the need) to consider the details. Here, graphical representations of a whole model on one page turned out to be useful, see Figure 31 for an example. For conciseness and precision we also favour mathematical descriptions as presented in Section 8.4.1.2 for MM-A. Overall, any type of model documentation found in Part I of this report has been found useful in the work of describing the models under development.

9 Current State of the Analysis and Further Development

In this chapter, simulation results that have been obtained using STOEMSys so far are discussed. In particular, these are simulations of a green investment impulse in the buildings sector (Section 9.1), which have also partly been presented in Chapter 3. Furthermore, the role of money supply is investigated in Section 9.2. At the end of this chapter, an outlook of further research that will be carried out using STOEMSys is given (Section 9.3).

9.1 Simulations of a Green Investment Impulse in the Buildings Sector

For the simulations shown in this section, macro-module S (MM-S, see Section 8.4.2) has been coupled to the simple buildings module (BM, see Section 8.4.3). A complete documentation of this model can be found in Chapter 10.

In total there are four agents, two in the macro-module (household, generic firm) and two in the sectoral module (retrofit firm, construction firm) and three goods (generic good, retrofitting, construction of green buildings), each of which is provided by the respective firm. Table 2 gives an overview. All agents own a part of the building stock, which consists of "brown" and "green" buildings. Retrofitting turns brown buildings into green buildings, and newly constructed buildings are always green.

Table 2: Agents

Agent	module	supplies	demands
Household	MM-S	labour	generic good, retrofitting, construction
Generic firm	MM-S	generic good	labour, generic good, retrofitting, construction
Retrofit firm	BM	retrofitting	labour, generic good, retrofitting, construction
Construction firm	BM	construction	labour, generic good, retrofitting, construction

For the generic good market the price dynamics through expectations and learning is active (Section 8.3). The construction firm plans to increase its production with GDP growth. The investment rate of the generic firm is the production growth rate, for the other firms it is given by the GDP growth rate (see Section 8.4).

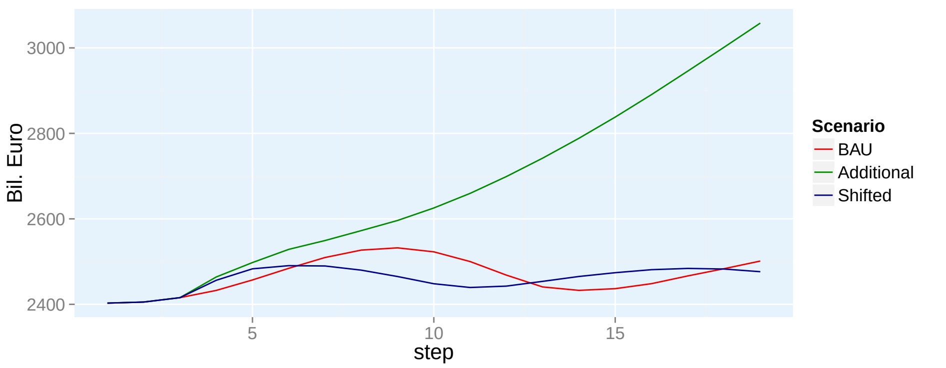
Three scenarios are simulated which differ in the household's decision for developing its buildings stock. In the business-as-usual (BAU) scenario, the household's disposable income Y^{disp} at each time step is distributed as a share of 80% for consumption of generic good ($\nu_G = 0.8$), 10% for construction of green buildings ($\nu_C = 0.1$), and 10% for retrofitting ($\nu_R = 0.1$). For the "Shifted" scenario, the consumption share is reduced by 1 percentage point for more retrofitting, $\nu_G = 0.79$ and $\nu_R = 0.11$ while the share for construction stays the same as $\nu_C = 0.1$. In the "Additional" scenario, the household spends as much for consumption and construction as in the BAU ($\nu_G = 0.8$ and $\nu_C = 0.1$) but at each time step retrofits 2% of its brown buildings stock independently of the disposable income. This means that the household can spend more money than its disposable income. In the simulations this is the case in the beginning while at later times the household spends less for retrofitting than in the other scenarios as the brown buildings stock decreases. The main difference between Shifted and Additional scenario is thus that in the Shifted scenario consumption is reduced in order to finance green investments while in the Additional scenario the consumption share of the disposable income is not altered, that is, additional investments are made for retrofitting. Table 3 gives an overview.

Table 3: Scenarios

	ν_G	ν_C	ν_R xb
BAU	0.8	0.1	0.1
Shifted	0.79	0.1	0.11
Additional	0.8	0.1	– [a]

[a] 2% of brown buildings are retrofitted independently of household's disposable income

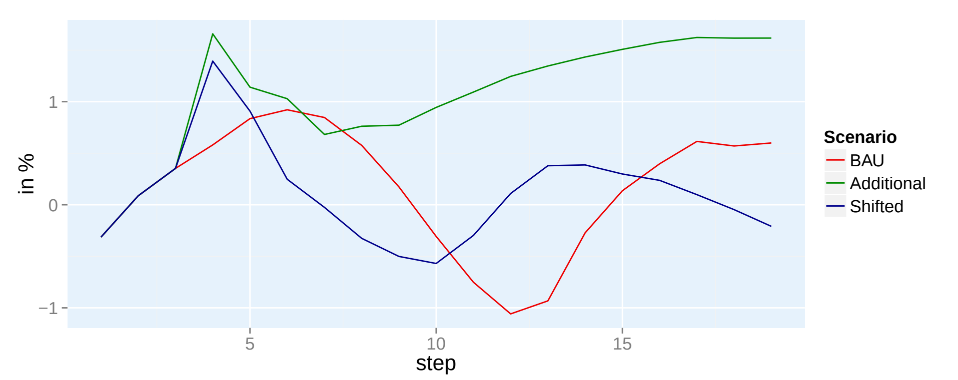
Figure 17: GDP



Figures 17 and 18 show GDP and GDP growth for all scenarios. The impulse for additional retrofitting is given after three time steps (years). For around the first eight time steps, the BAU scenario shows a reasonable GDP development with growth rates between 0% and 1%. However, for longer runs the observed dynamics show some problems. It is still not clear what they arise from but they certainly have to do with the elaborate price dynamics introduced through expectations and learning since for simulations with other settings for the generic firm's production planning the negative growth rates are not observed. In general, simulations with this price dynamics turned out to be very sensitive to initial settings, see Section 9.3.1 for further discussion.

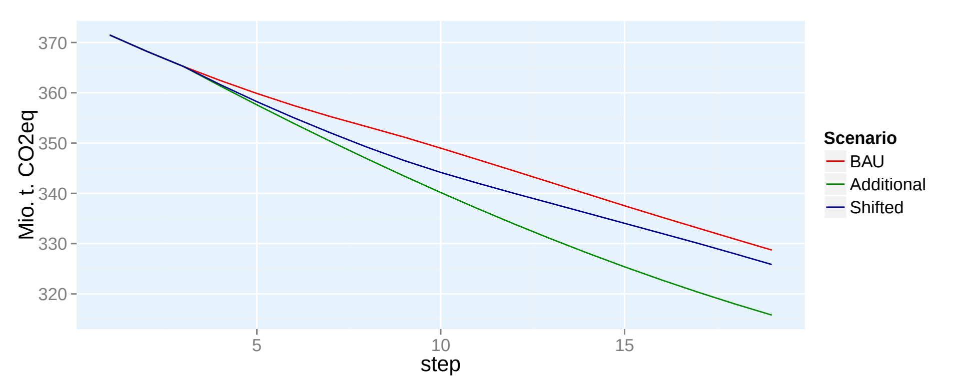
The scenarios with faster retrofitting, the Additional and the Shifted scenario exhibit very different features. While in the Shifted scenario, where green investments replace consump-

Figure 18: GDP growth



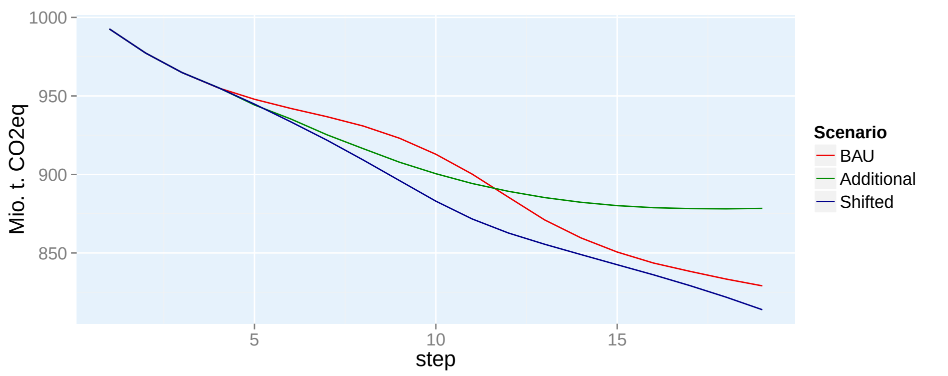
tion, GDP growth stays in the same range as for the BAU, in the Additional scenario significantly higher growth is observed. In order to decide whether this growth, which is driven by "green" investments, would classify as "green growth" one has to look at the GHG emission, which are shown in Figures 19 and 20.

Figure 19: Buildings emissions



For the buildings emissions (Figure 19) the situation is clear: the faster brown buildings are turned into green ones, the faster the emission reduction although in the Additional scenario due to higher growth the buildings stock increases faster. That means that in the buildings sector efficiency improvements overcompensate the higher stock growth. For the overall emissions, the results are shown in Figure 20. Higher GDP growth, as in the Additional scenario, means a higher overall production, especially of the generic good, that also causes higher emissions. That explains that in the Shifted scenario (more retrofitting at lower consumption) overall emissions are below the ones of the Additional scenario. Until around time step 11, BAU emissions are highest, then Additional emissions take over. However, here only in the

Figure 20: Emissions



buildings sector a green investment impulse has been modelled. The situation will almost certainly change if the same is applied to other emission-relevant sectors (see also Section 9.3.2). Beyond that, there are still some difficulties with the dynamics of the system after the first decade (see above), so as soon as these are fixed, emission trajectories will also change.

Figure 21: Supplied vs. sold quantities

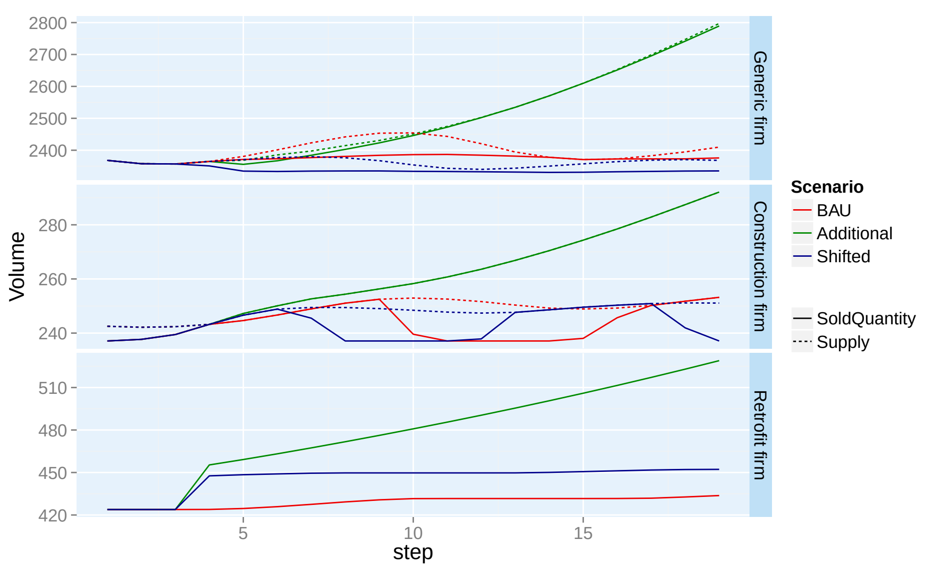
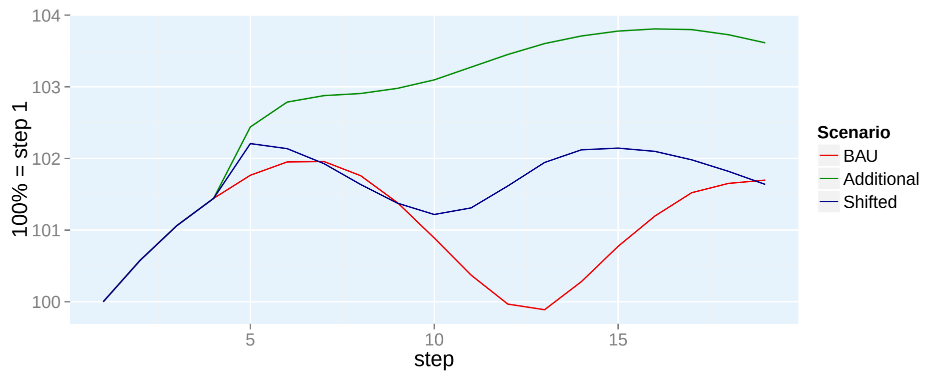


Figure 21 illustrates that our economic system does not have to be in an economic equilibrium (i.e. supply equals demand). Here, supplies and sold quantities of all three goods are shown. Only for retrofitting – where the firm knows about the demand before producing – the two respective curves overlap all the time.

Figure 22: Price of generic good



Prices of retrofit and construction are set to 1 (see Section 8.4.3). The price for the generic good is shown in Figure 22. It arises from the profit optimization of the generic firm as described above (Section 8.3) but in general the price level is also influenced by the relation of productivity and money supply in the system. These kind of investigations are beyond the scope of this project. However, it is one of the outcomes that introducing an out-of-equilibrium price dynamics based on expectations and learning requires fiat money. Some first simulations have been done with STOEMSys to examine the role of money supply in the system. They are the topic of the next section. Planned further development in this area is briefly sketched in Section 9.3.3.

9.2 Money Supply and Inflation

In the course of this projec, it has been observed that when a price development scheme based on expectations and learning (as described in section 8.3) is implemented, fiat money becomes necessary. In the most simplified version of a model with this price dynamics one could think of e.g. leaving out capital as a production factor. However, money is needed even in the most simplified setting to deal with the fact that expectations may be wrong and thus equilibrium (in the sense "supply equals demand") is not necessarily obtained in the goods market. Therefore, first simulations have been carried out to see how different rules of money supply (i.e. different implementations of the central bank) affect the macro-economic dynamics. The observations presented in this section have been performed with macro-module A (MM-A) alone, i.e. without any coupling to a sectoral module. They go beyond what was originally proposed as the scope of this project.

All the equations that describe MM-A as a dynamic system are given in section 8.4.1.2. Money supply, i.e. action of the central bank, is described by the terms X_t and Y_t in Equations (25) and (26), respectively, which describe the monetary holdings of household ($m^{(H)}$) and firm ($m^{(F)}$). The equations are

$$\begin{aligned} m^{(H)}_{t+1} &= m^{(H)}_t + w_{t+1} \cdot L^{(M)}_{t+1} + p_t \cdot K_t \cdot d_{t+1} - p_{t+1} \cdot C^{(R)}_{t+1} + X_t \\ m^{(F)}_{t+1} &= m^{(F)}_t + p_{t+1} \cdot (q^{(M)}_{t+1} - I^{(R)}_{t+1}) - w_{t+1} \cdot L^{(M)}_{t+1} - p_t \cdot K_t \cdot d_{t+1} + Y_t. \end{aligned}$$

In the following, observations are reported for an implementation of the dynamical system given by (1)-(28) with different versions of terms X_t and Y_t in (25) and (26).

9.2.1 Constant Amount of Money

A constant amount of money in the system is obtained by setting $X = Y = 0$, i.e.

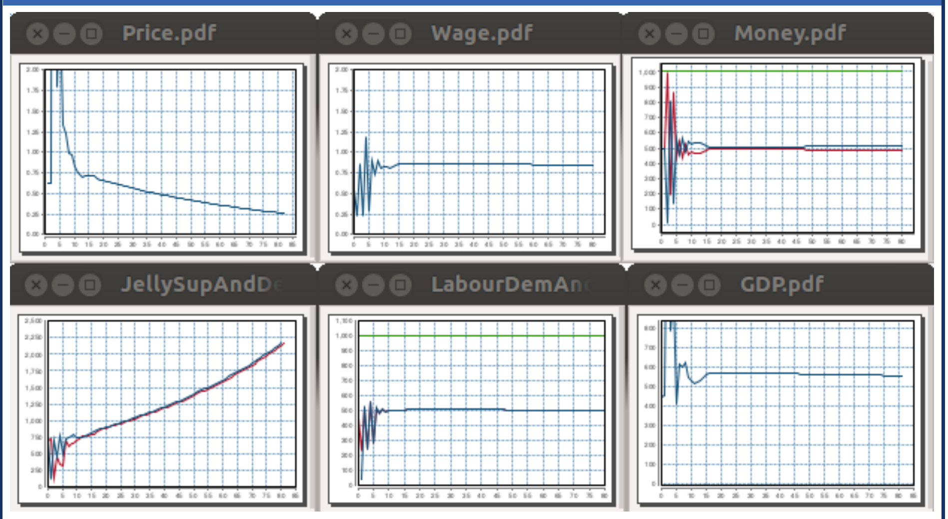
$$m_{t+1}^{(H)} = m_t^{(H)} + w_{t+1} \cdot L_{t+1}^{(M)} + p_t \cdot K_t \cdot d_{t+1} - p_{t+1} \cdot C_{t+1}^{(R)} \tag{37}$$

$$m_{t+1}^{(F)} = m_t^{(F)} + p_{t+1} \cdot (q_{t+1}^{(M)} - I_{t+1}^{(R)}) - w_{t+1} \cdot L_{t+1}^{(M)} - p_t \cdot K_t \cdot d_{t+1} \tag{38}$$

which also means that $\Delta m^{(H)} = m_{t+1}^{(H)} - m_t^{(H)} = -\Delta m^{(F)} = -(m_{t+1}^{(F)} - m_t^{(F)})$.

Simulation results are shown in Figures 23 and 24. The system reaches an exponential growth of jelly supply and demand (the market clears) while the price level decreases exponentially with the same rate, a clearing labour market with constant labour supply and demand at a stable wage level, and a stable level of GDP.

Figure 23: Constant Amount of Money



From left to right: jelly price, wage, monetary holdings (firm: blue, household: red, total: green), next row: jelly supply (blue) and demand (red), labour demand (blue) and supply (red), and GDP for the case with a constant amount of money in the system.

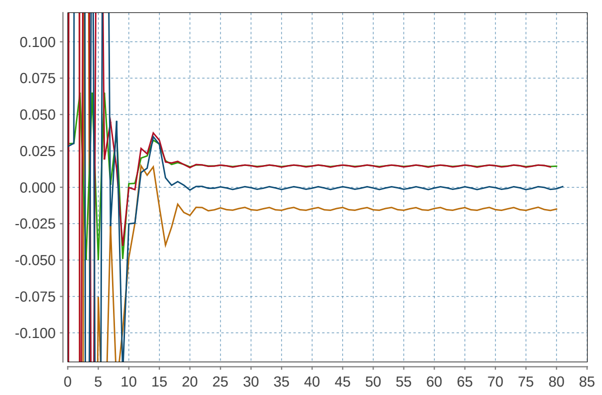
9.2.2 Money Increase on Household's Side

At each time step, a constant fraction x of the total amount of money is given to the household, i.e. $X = x \cdot (m_t^{(H)} + m_t^{(F)})$ and $Y = 0$, which means for the monetary holdings of household and firm that

$$m_{t+1}^{(H)} = m_t^{(H)} + w_{t+1} \cdot L_{t+1}^{(M)} + p_t \cdot K_t \cdot d_{t+1} - p_{t+1} \cdot C_{t+1}^{(R)} + x \cdot (m_t^{(H)} + m_t^{(F)}) \tag{39}$$

$$m_{t+1}^{(F)} = m_t^{(F)} + p_{t+1} \cdot (q_{t+1}^{(M)} - I_{t+1}^{(R)}) - w_{t+1} \cdot L_{t+1}^{(M)} - p_t \cdot K_t \cdot d_{t+1}. \tag{40}$$

Figure 24: Growth Rates to Figure 23



Growth rates for GDP (blue), output (red), capital stock (green) and price (yellow) for the two runs with constant amount of money.

Figure 25 shows a simulation. Here x was chosen as $x = \tilde{g} = 0.03$ with $\tilde{g}$ being the targeted capital growth rate (see Equation (1)). This means that the money growth is of a similar order as the capital growth and therefore the potential output, since technological progress also growths with the net investments (Equation (27)). As then expected, the price level is not far from being constant. Output, demand, wage, and GDP increase exponentially.

Figure 25: Increase on Household's Side

From left to right: jelly price, wage, monetary holdings (firm: blue, household: red, total: green), next row: jelly supply (blue) and demand (red), labour demand (blue) and supply (red), and GDP for the case with an increasing money supply where extra money is given to the household with a constant rate at each time step.

9.2.3 Money Increase on Firm's Side

The scenario that a central bank increases the money supply by giving money to the household is very far from reality. A bit more realistic is a central bank that finances the firm's investments.

The idea of the following simulations where the money supply is increased on the firm's side is that net investments are financed by the central bank while replacement investments are paid from the firm's income. Therefore, for the simulations shown in this section, Equation (2) was changed to

$$L_{t+1}^{(D)} = \arg\min_{L} \left|(\rho(L) - \delta \cdot K_t)\frac{\kappa_t}{\rho(L)^{\theta_t}} - \omega_t^{(e)}(L) \cdot L - p_t^{(M)} \cdot K_t \cdot d_t\right|. \tag{41}$$

That means that the firm still tries to "zeroize" the difference of income and expenditures, but net investments are no longer considered expenditures.

9.2.3.1 Central Bank Finances Net Investments

For the case that the central bank pays the net investments to the firm, in Equations (25) and (26) $X = 0$ and $Y = p_{t+1}(I_{t+1}^{(R)} - \delta \cdot K_t)$, i.e. the monetary holdings of household and firm develop as

$$\begin{aligned} m_{t+1}^{(H)} &= m_t^{(H)} + w_{t+1} \cdot L_{t+1}^{(M)} + p_t \cdot K_t \cdot d_{t+1} - p_{t+1} \cdot C_{t+1}^{(R)} && (42)\\ m_{t+1}^{(F)} &= m_t^{(F)} + p_{t+1} \cdot (q_{t+1}^{(M)} - \delta \cdot K_t) - w_{t+1} \cdot L_{t+1}^{(M)} - p_t \cdot K_t \cdot d_{t+1}. && (43) \end{aligned}$$

Figures 26 and 27 depict the simulation results. Although now the money supply increases with the productivity (which here increases with net investments), the price level is still slightly decreasing over time. This may be due the temporal delay of price adjustment and to the increase of labour.

9.2.3.2 Money Supply with Inflation Target

A stable price level is expected if the money supply increases with productivity (i.e. in our implementation, with the net investments). In the simulations shown in the last paragraph this can (roughly) be observed. As a first approach to implementing a fixed central bank inflation target, the money supply is increased at the rate of capital growth plus the inflation target $\tilde{i}$, i.e. $X = 0$ and $Y = (m_t^{(F)} + m_t^{(H)}) \cdot \left(\frac{I_{t+1}^{(R)} - \delta \cdot K_t}{K_t} + \tilde{i}\right)$. For the monetary holdings of the agents that means

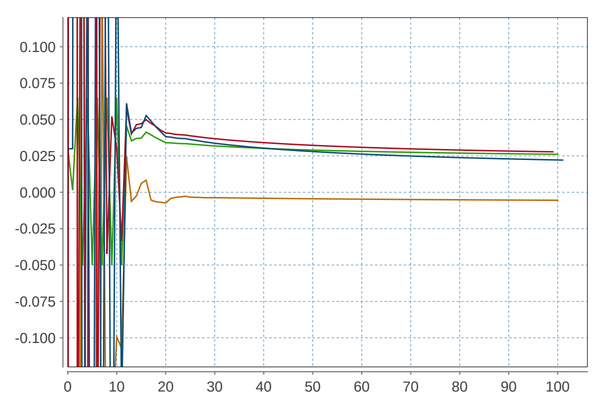
$$\begin{aligned} m_{t+1}^{(H)} &= m_t^{(H)} + w_{t+1} \cdot L_{t+1}^{(M)} + p_t \cdot K_t \cdot d_{t+1} - p_{t+1} \cdot C_{t+1}^{(R)} && (44)\\ m_{t+1}^{(F)} &= m_t^{(F)} + p_{t+1} \cdot (q_{t+1}^{(M)} - I_{t+1}^{(R)}) - w_{t+1} \cdot L_{t+1}^{(M)} - p_t \cdot K_t \cdot d_{t+1} \\ &\quad +(m_t^{(F)} + m_t^{(H)}) \cdot \left(\frac{I_{t+1}^{(R)} - \delta \cdot K_t}{K_t} + \tilde{i}\right). && (45) \end{aligned}$$

Figures 28 and 29 show simulation results for $\tilde{i} = 0.02$. GDP, output, wages and prices increase (rather) exponentially. Output and capital stock grow with around 5% which is the

Figure 26: Central Bank Finances Net Investments

From left to right: jelly price, wage, monetary holdings (firm: blue, household: red, total: green), next row: jelly supply (blue) and demand (red), labour demand (blue) and supply (red), and GDP for the case with an increasing money supply where extra money of the value of net investments is given to the firm at each time step.

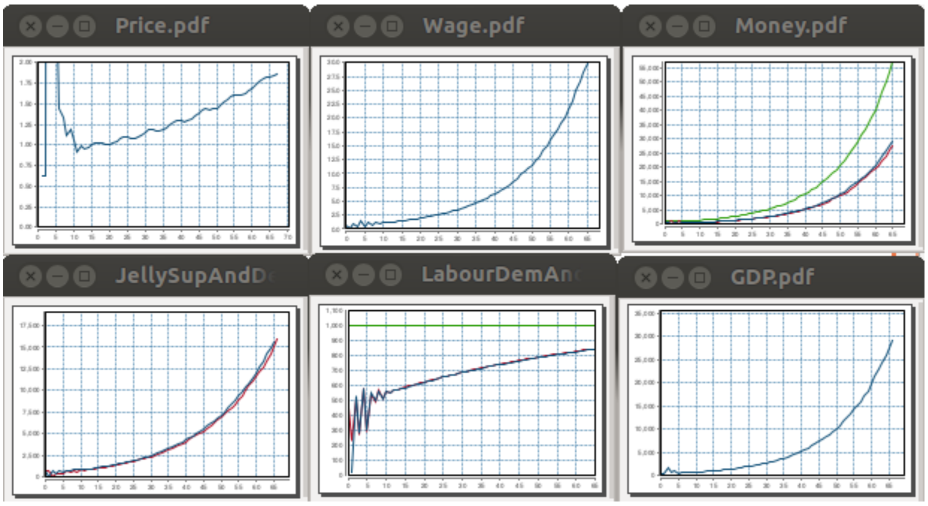
Figure 27: Growth Rates to Figure 26



Growth rates for GDP (blue), output (red), capital stock (green) and price (yellow) for the simulation results shown where the money given to the firm equals the value of net investments.

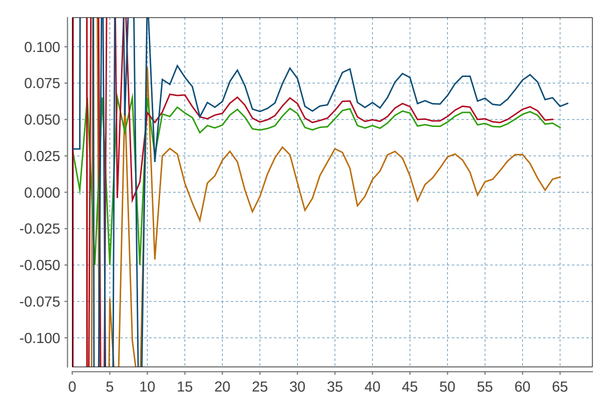
sum of the firm's capital growth target $\tilde{g} = 0.03$ and the inflation target $\tilde{i} = 0.02$. Inflation (price growth) oscillates between 0% and 0.25%.

Figure 28: Money Supply with Inflation Target



From left to right: jelly price, wage, monetary holdings (firm: blue, household: red, total: green), next row: jelly supply (blue) and demand (red), labour demand (blue) and supply (red), and GDP for the case with an increasing money supply where extra money is given to the firm that increases the total amount of money by the capital growth rate plus an inflation target rate of 2%.

Figure 29: Growth Rates to Figure 28



Growth rates for GDP (blue), output (red), capital stock (green) and price (yellow) for an inflation target of 2%.

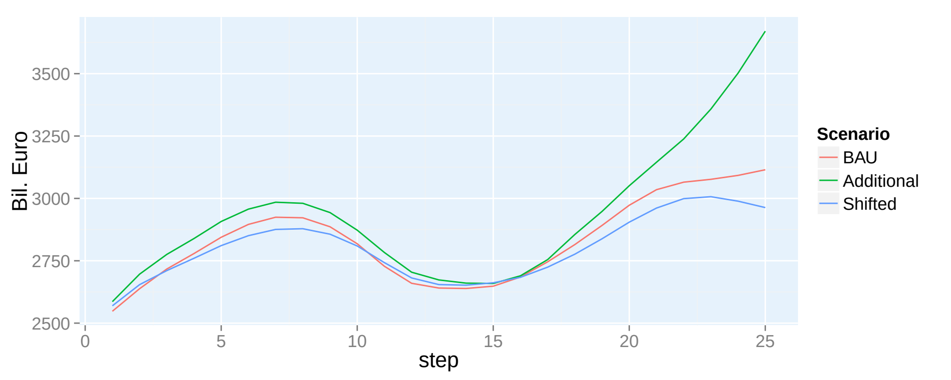
9.3 Further Development

The work on STOEMSys will be continued beyond the term of this project. There are both more academic and more simulation-like problems for the tackling of which our modelling system provides a good tool or starting point.

9.3.1 Calibration and Dynamics

In the first simulations, it has been observed that the model is still very sensitive to calibration changes and there are problems with initialising the dynamics through expectations and learning. For example, if in the simulations shown in Section 9.1 the initial demand expectations of the generic firm are changed, instead of the behaviour shown in Figure 17 a GDP as displayed in Figure 30 is obtained. Thus depending on the choice of initial parameters of the firm's expected demand function (see Section 8.3) oscillations can be observed in dynamical behaviour of the system. The origins of these are still not clear. In the future, it will be investigated whether there is a transient state in the beginning of the simulations; if so, calibration should be done in a way that the calibration values are reached after the system has overcome this transient state.

Figure 30: GDP with oscillations



Considering the existence of a transient state leads to the question of identifying stable states, i.e. stable fixed points of the dynamic system. While in the simulations stable states can be observed (which do not necessarily have to be equilibria in the economic sense), an analytic determination of stable states is very challenging since even for a quite simplistic model as e.g. macro-module A (MM-A) alone there are already 15 state variables (see Section 8.4.1), all of which are dependent of almost all of them, as shown in Table 4. Therefore, one of the future tasks is to explore the parameter space (e.g. using SimEnv, see Section 7.4.2) to "experimentally" find stable states of the dynamic system under considation.

9.3.2 Sectoral Integration

Two directions for further work on sectoral integration are the integration of several sectors, and the refinement of a given sector with the help of experts and their models.

STOEMSys model simulations presented in Chapter 3 were obtained from models consisting of a macro-module and only one sectoral module of the buildings sector. While very important in terms of fixed capital share of the economy, the buildings sector is not the most important one in terms of emissions. It is thus certainly desirable to include further sectors into the analysis, notably energy and transport. The effect of this will not just be summing up different emission reductions and growth effects since due to the integration of macro-economic effects via the macro-module, feedback effects are also taken care of. This is especially in-

Table 4: Dependences of MM-A State Variables

	g_t	(κ_t, θ_t)	(z_t, ξ_t)	K_t	d_t	$m_t^{(F)}$	p_t	η_t	$m_t^{(H)}$	$q_t^{(M)}$	$q_t^{(D)}$	w_t	$L_t^{(S)}$
g_{t+1}	X	XX	XX	X	X	X	X	X	X	X			
$(\kappa_{t+1}, \theta_{t+1})$	X	XX	XX	X	X	X	X	X	X		X		
(z_{t+1}, ξ_{t+1})	X	XX	XX	X	X	X	X					X	X
K_{t+1}	X	XX	XX	X	X	X	X	X	X				
d_{t+1}	X	XX	XX	X	X	X	X	X	X				
$m_{t+1}^{(F)}$	X	XX	XX	X	X	X	X	X	X				
p_{t+1}	X	XX	XX	X	X	X	X	X					
η_{t+1}	X	XX	XX	X	X	X	X	X					
$m_{t+1}^{(H)}$	X	XX	XX	X	X	X	X	X	X				
$q_{t+1}^{(M)}$	X	XX	XX	X	X	X	X	X	X				
$q_{t+1}^{(D)}$	X	XX	XX	X	X	X	X	X	X				
w_{t+1}	X	XX	XX	X	X	X	X						
$L_{t+1}^{(S)}$	X	XX	XX	X	X	X	X						

teresting with respect to the "rebound effect" discussion and may shed new light on it from a macro-economic perspective.

For the second direction, first coordination meetings have been held to prepare the connection of an existing buildings sector model to the STOEMSys framework. The exchange with experts from Ecofys, working on the Built Environment Analysis Model (BEAM^2), began, as is natural, by getting to know each others' models to the extent necessary.

Very briefly, BEAM^2 is a calculation model drawing on a huge database. It can be used to analyse for example energy demands, GHG emissions and costs for space heating and cooling, hot water and auxiliary energy in buildings, and can be applied flexibly to different levels of aggregation for building stocks at country, regional or city levels.

For the cooperation, Europe was chosen as the level for the analysis. The next step planned is to integrate time series of data from BEAM^2 in the interface of the macro-module for policy simulation MM-S, described in Section 8.4.2 and documented in Section 10, to "replace", so to say, the simple buildings module. This means, whenever a buildings module agent interacts with a macro-module agent, the information concerning the buildings module agent is provided by BEAM^2 results. The STOEMSys macro-module needs to be extended for this data import, however, this should not be a difficult task. In particular, data import will be necessary in the following steps:

- Retrofit market: BEAM^2 can supply the price for retrofitting.
- Labour market: from investment into retrofitting, BEAM^2 can supply necessary labour, i.e. in STOEMSys terms the labour demanded by the retrofit firm.
- Generic good and green buildings markets: BEAM^2 can supply the investment demands of sector module firms.

From the point of view of the BEAM^2 model, which comprises information at a very high level of detail, the data to be imported into MM-S may seem very aggregate, but this is meant as a first and “proof-of-concept” step for complementing a STOEMSys macro-module with an existing sectoral model.

9.3.3 Government and Finance

The macro-modules already contain a (quite simplistic) central bank. Some simulations of different central bank actions are shown in Section 9.2. So far, the government has only been present in the simulations as the source of an exogenous investment (retrofitting) impulse (see Chapter 3 and Section 9.1).

Fiscal and monetary policies are relevant for climate and GHG emissions. For modelling with STOEMSys, the interesting policy cases are:

- *Green fiscal stimulus*: It is supposed that a public investment program targeted at green goods and green capital is realised, in the same spirit like in the first proof-of-principle simulations shown above for the buildings sector but more extensive, targeting other sectors as well. Political proposals around that are called "Green New Deal" etc.
- *Unconventional monetary policy*: The idea is to model “green quantitative easing”, i.e. the central bank buys green bonds or green infrastructure-backed securities.

Important for modelling these policies is that we have on the one hand GHG emissions and the specific information about climate-relevant sectors, and on the other hand a macro-module with descriptions of the financial sector. STOEMSys as a framework is structured for that because it combines the sectoral view for origins of emissions with the macro-economic perspective. In the future, the modules will be further developed to address these questions at the intersection of climate policy and financial aspects.

10 Documentation of a Macro-Module Coupled with Buildings Sector

The previous project reports presented a specification for a prototype model, the prototype (Jaeger et al. 2013) and an interim version of a model consisting of a macro-module for policy simulation together with a simple buildings module (Jaeger et al. 2014). This model has been further developed within STOEMSys.

This chapter documents the model according to the Dahlem ABM documentation guidelines (Wolf et al. 2013a). Since this documentation shall be readable as a stand-alone document, the section may duplicate information both from earlier sections in this report (in particular, Section 8.4.2 and 8.4.3) as well as from the corresponding documentation of prototype (Jaeger et al. 2013 Section 8) and interim version (Jaeger et al. 2014 Section 6).

The guidelines structure the documentation into an overview, design concepts and the functional specification, as detailed by Table 5. For each issue, the documentation guidelines provide a set of questions, which are answered in the following text. Where questions are displayed at the beginning of sections, these are taken from the guidelines.

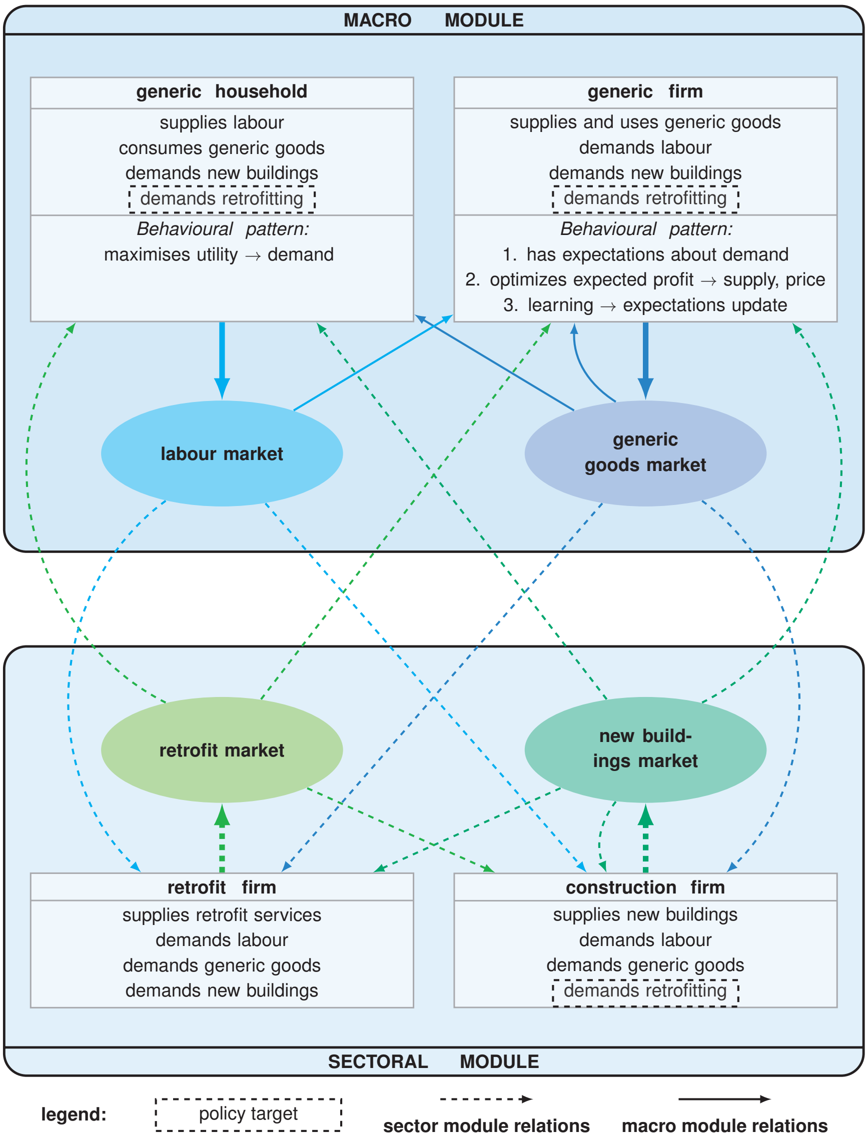
Table 5: Dahlem guidelines summary template

Overview (max. 3 pages)	Rationale Agents Other entities Boundaries Relations Activities
Design Concepts (max. 3 pages)	Time, activity patterns and activation schemes Interaction protocols and information flows Forecasting Behavioural Assumptions and Decision Making Learning Population Demography Levels of Randomness Miscellaneous
Functional Specification	Description of Agents and Other Entities, action and interaction Initialization Run-time input

10.1 Overview

The model is an implementation in the Sustainability Transition Open Economic Modelling System (STOEMSys). For a first impression about agents and their interaction, consider Figure 31.

Figure 31: STOEMSys MMS & BM



STOEMSys macromodule for policy simulation with simple buildings module

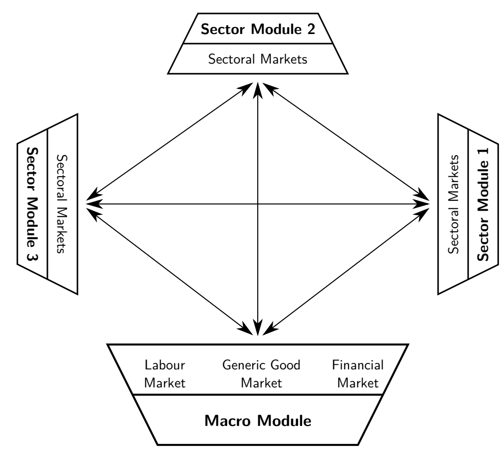
10.1.1 Rationale

What is the object under consideration? What is the intended usage of the model? Which issues can be investigated?

As an element of the STOEMSys, the model focuses on how climate policy can trigger a sustainability transition. The particular example under study is an investment impulse into retrofitting buildings.

At the same time, it illustrates the modular architecture of STOEMSys models, as displayed in Figure 32. To show how in this architecture an agent-based macroeconomic module can complement detailed sector-specific models of emission relevant sectors to assess costs and benefits of climate and energy policy measures for the German economy, a macroeconomic module (MM) is combined with a simple buildings module (BM).

Figure 32: Modular Architecture



The model builds on prototype and interim version of the German Green Growth Model. While the prototype's main feature was simplicity, in the interim version price dynamics with the corresponding mechanisms of expectation and learning were added. The model presented here further refines these dynamics.

10.1.2 Agents

What kind of agents are considered in the model? Is there a refined taxonomy of agents? Are there agent groupings which are considered relevant?

For simplicity, aggregate agents are used. These are not to be understood as representative agents as used in many standard economics models, in the sense of perfectly rational agents with complete information. An aggregate agent here rather summarizes the behaviour of what in reality would be a large number of agents, who have limited knowledge and bounded rationality (see Sections 10.2.3 and 10.2.4 below). However, the model structure would also allow to implement larger numbers of disaggregated agents.

The agents are the decision-making entities in the model, taking production, investment, or consumption decisions, producing or consuming goods and interacting on markets. In particular, the model has four agents, two agents in each module:

MM Agents in the macroeconomic module are a generic firm and a (generic) household.

BM The buildings module has two agents: a construction firm and a retrofit firm.

It may seem exaggerated to define a taxonomy of four agents – however, note that one could consider the three firms as a group of agents, that are similar in their activities while the household pursues different activities (see Section 10.1.6). Within the group, each firm represents a sector (construction, retrofit, respectively an aggregate "rest of the economy" sector).

10.1.3 Other Entities

What are the other entities which are time-evolving but not decision-making?

The modules do not represent decision-making entities but structure the model and provide the economic (or functional) resolution and are therefore considered as other entities. The same is true for sectors. Each module can consist of several sectors, depending on the granularity chosen. Sectors play an important role in conceptualizing economic systems, and in their representation, STOEMSys models relate back to standard economic models that use input-output tables from national statistics to capture interactions in the production structure within the economic system. Sectors evolve over time and their statistics may influence decisions by the agents in the model (as in the case where a firm bases a decision on the current growth rate observed in a sector). The macroeconomic module contains only one sector with only one good, referred to as the generic good.

As the focus of the model is a retrofit investment impulse, buildings are differentiated according to energy efficiency and hence emissions: there are “brown” buildings with high emissions and “green” buildings with low emissions. Given that the buildings module is simple, just these two kinds of buildings are considered. One could consider buildings as time evolving entities as brown buildings can be retrofit into green buildings.

10.1.4 Boundaries

What are additional inputs to the model at run-time?
Which outside influences on the model are hence represented?

The model does not use additional inputs at run-time. At initialization, the model user can choose a policy input to analyse the policy influence on the system. This input is the share of brown buildings that agents in the model decide to retrofit.

10.1.5 Relations

What kind of relationships structure the agents’ interactions?
To which extent do these represent institutions?

Agents interact in markets where they are related as buyers and sellers. The market characteristics can differ depending on the nature of the product, the agents and their strategies as well as the institutional setting which defines the market.

The given model has two kinds of markets, a labour market and three goods markets for generic good, construction and retrofitting of the built environment. Agents negotiate in these markets to establish the respective amounts of labour and goods exchanged for the production processes and for consumption. Thus, they may influence each other’s expectations by providing observations with each iteration.

10.1.6 Activities

What kind of actions and interactions are the agents engaged into?

The agents, described in Section 10.1.2, are engaged into the following actions and interactions:

MM The household provides labour to all firms and consumes the generic good.
The generic firm produces and supplies the generic good, using employed labour and

capital from all three sectors.
Both agents additionally invest into building new (“green”) buildings and retrofitting their stock of “brown” buildings.

BM The retrofit firm “produces” the service to improve the energy efficiency of buildings by converting “brown” buildings to “green” ones. Like the generic firm and the household, it can invest into building new (green) buildings and into retrofitting its stock of brown buildings. It uses labour and capital from all other sectors.
The construction firm produces new “green" buildings[11]. It may also invest into retrofitting its own brown buildings. It also uses labour and capital from all three sectors.

Depending on the polices implemented to trigger investments into retrofitting buildings, all agents adjust their retrofit demand. The household updates its money holdings and decides to buy goods or invest into buildings or retrofitting. Firms update their desired production and update their investment accordingly. All agents carry out accounting procedures.

10.2 Design Concepts

10.2.1 Time, Activity Patterns, and Activation Schemes

What is the basic sequence of events in the model? Are activities by agents triggered by a central clock or by actions respectively messages sent by other agents? What is the interpretation of one time unit in the model?

Time is modelled discretely; a period, consisting of several steps, provides the model’s temporal resolution. The real time interpretation of a period in the model is the unit of time taken for the computation of flows used as data (e.g. production). Actions are triggered by the “central clock” provided by the counting of periods.

The sequence of steps within a period, representing different market transactions and activities such as production or accounting is fixed. See Table 7 in Section 10.3.5 for the order of markets taking place and the preparatory actions agents carry out before entering a market.

10.2.2 Interaction Protocols and Information Flows

What are the general properties of the protocols governing the interaction between agents? How is determined which agents can interact with each other? What kind of information is available to each agent? If agents interact within institutional frameworks like firms or markets, what are the main properties of these institutions?

Agents interact bilaterally in the different markets. Since agents are aggregate, all agents mutually interact (local interactions between smaller groups of agents and matching of agents could apply in a version with disaggregated agents). The information the agents exchange in the market interaction are the supply, demand and asked, respectively, maximally accepted price. Sellers use a “first comes, first served” policy, and the order in which sellers and buyers enter the market is fixed.

[11] There is no production of “brown” buildings, as the building code for new buildings in Germany require new buildings to be “green”. This means, the stock of brown buildings is given at the beginning of a simulation run, as input from the data-set, and may decrease but not increase. When representing different countries, or refining the classification of buildings, production of several types of new buildings may need to be considered.

10.2.3 Forecasting

Are agents in the model forward looking or purely backward looking? If agents are forward looking, what is the basic approach to modelling forecasting behaviour?

Agents are both forward and backward looking, decision rules can be chosen by the model user.

Forward looking decision rules are modelled in simple ways: Given that agents are aggregate, the model tries to capture relevant dynamics for conventions and coordination between agents. For example, firms may determine their desired production, and hence their investment levels, depending on the growth of capital. This represents sticking to the growth convention in place at that moment.

Backward looking decision rules are based on projecting past observations onto the future. Agents use expectations for issues of concern that they do not have complete information about, e.g. a firm has expectations about the demand for its product.

10.2.4 Behavioural Assumptions and Decision Making

Based on which general concepts is decision making behaviour of the different types of agents modelled? If the decision making of certain agents is influenced by their beliefs, how are these beliefs formed?

Agents have bounded rationality and gain only partial information about their environment in their interactions. As mentioned, their operating decisions can be based on relevant (macroeconomic) dynamics or they can result from a learning routine that takes past observations into account.

10.2.5 Learning

Are decision rules of agents changed over time? If yes, which types of algorithms are used to do this?

For the production technologies, learning by doing is represented by an efficiency parameter that increases with investment.[12]

Individual learning of agents is implemented for the generic firm. Over time, it gathers information about the demand for its good and it uses this information to improve its expectations of the consumers' demand.

Implicitly, any adaptation of strategies that agents undertake, based on observations (for example, adapting growth of the desired production to previously observed growth) can be considered a representation of how agents learn.

10.2.6 Population Demography

Can agents drop out of the population and new agents enter the population during a simulation run? If yes, how are exit and entry triggered?

The population of aggregate agents is fixed.

[12] For detail on this well established mechanism, see for example Jaeger et al. 2013, Section 6 on model features for the German Green Growth model.

10.2.7 Levels of Randomness

How do random events and random attributes affect the model?

The model is deterministic.

10.2.8 Miscellaneous

Any important aspects of the used modelling approach that do not fit any of the items above should be explained here, for example, mathematical properties of the model.

Two important design concepts behind the model derive from the the fact that the model is an implementation within the STOEMSys: a modular structure to allow the economy-wide analysis of costs and benefits of energy and climate policy measures targeted to specific emission-relevant sectors; and the representation of several possible growth paths in order to allow for the identification of win-win strategies, in particular, a sustainability transition.

10.3 Functional Specification

This section provides a detailed description of the model, which focuses on the markets and modules in which the different actions take place. For information about the concrete implementation and about how it can be extended, see Section 8.5.

Table 6 gives an overview of the variables of the agents. It names each state variable with its notation and assigns it to the firm, to the household, or to both of them respectively. In many formulas, these variables will have a (subscript) index t to denote the time. The index $t-1$ denotes the value of a variable of the previous time step. Superscripts assign a firm or a good that the variable belongs to. Variables and methods of the code are highlighted by using the `sans serif` font, the types of the prototype implementation (the agents, markets and goods) by using the SMALLCAPS font.

The four different kind of goods GENERICGOOD, GREENBUILDINGS, BROWNBUILDINGS and RETROFIT will be denoted by *Gen*, *G*, *B* and *R* respectively. These goods are traded via markets. In this specification X always denotes a member of the set of goods:

$$X \in \{Gen, G, B, R\}.$$

Any firm produces only one special good: The generic firm (GenF) produces the generic good (Gen), the retrofit firm (RF) "produces" the retrofit service (R) and the construction firm (CF) produces green buildings (G). This gives three tuples of (W, X_W) where

$$W \in \{GenF, RF, CF\}$$

is a firm and X_W the produced good of firm W. We get the set of tuples

$$Z_W = (W, X_W) \in \{(GenF, Gen),\ (RF, R),\ (CF, G)\}.$$

Many decisions of the agents can be assigned to a market, e.g. a firm decides the amount of goods that it wants to produce before it enters the labour market. Therefore, the list of

Table 6: State and auxiliary variables of firm and household or of their interaction

firm variable	firm notation	both notation	household variable	household notation
state variables				
capital		K	capital (buildings)	
capital growth	g			
efficiency	η			
expected demand coefficients	(κ, θ)			
desired production	q_d			
capacity utilization	ξ			
			desired consumption	C_d
monetary holdings	(M)		monetary holdings	m
auxiliary variables				
desired retrofit service		R_d	desired retrofit service	
retrofitted buildings		R	retrofitted buildings	
labour demand	L_D		labour supply	(L_S)
market labour		L_m	market labour	
wage (offered)	w_D		wage (asked)	(w_S)
market wage		(w_m)	market wage	
desired investment	I_d			
(actual) investment	I			
(actual) production	q			
supply	q_S		demand	q_D
quantity (sold)		q_m	quantity (bought)	
price for supply	p_S		price for demand	p_D
market transaction price		p_m	market transaction price	
turnover (earned)		(P)	turnover (spent)	
			income	Y
			disposable income	Y^{disp}
gdp growth	$\hat{g}$			
			(actual) consumption	(C)
expected profit	π_e			
invariant values				
output elasticities	α, β, γ			
depreciation coefficients	$\delta_\alpha, \delta_\beta, \delta_0$			
learning coefficients	ϕ, ψ, γ, b			
normal capacity utilization	ξ_0			
retrofit share		μ	retrofit share	
			consumption distribution	$\nu^{Gen}, \nu^{G}, \nu^{R}$
wage adjustment factor	ω			
return on capital	r			
			savings rate	s

When the notation of a variable is set into (braces), the variable is mentioned in the specification without using the notation.

steps in a single period shrinks mainly to the different market negotiations. Additionally, there is a `production` step and an `accounting` step. The order of market negotiations, the `production` and `accounting` step is shown in the following code fragment:

```
retrofitMarket.negotiateFirstComeFirstServed
labourMarket.negotiateFirstComeFirstServed
allFirms.foreach{_.production()}
stats.updateGDP()
genericGoodMarket.negotiateFirstComeFirstServed
greenBuildingsMarket.negotiateFirstComeFirstServed
allAgents.foreach{_.accounting()}
```

But there are also some concepts in the model that cut across steps. We begin the specification with an explanation of those concepts, before we continue with the description of the different markets in 10.3.5, followed by the specification of the remaining steps.

10.3.1 Capacity Utilization

A firm can vary the utilization of the capital stock. This allows it to respond to demand shocks spontaneously not only by adjusting labour input, but also by adjusting the capacity utilization, which results in a higher or lower depreciation of the capital.

The capacity utilization implemented in the model adds a fixed depreciation to the depreciation function $\delta(\xi)$, so that the capital depreciates even if the utilization is zero. Additionally, a normal capacity utilization ξ_0 is introduced, so that the depreciation $\delta(\xi)$ matches the normal deprecation rate δ_0, which is given as exogenous variable: $\delta(\xi_0) = \delta_0$.

By limiting ξ to the interval [0, 1], we get for the capacity utilization $\frac{\xi}{\xi_0}$ the maximal utilization of $\frac{1}{\xi_0}$.

The fixed deprecation rate is defined as a fraction of δ_0 using the coefficient δ_α with $0 \leq \delta_\alpha \leq 1$, so that $\delta(0) = \delta_\alpha\delta_0$. Similar, if $\xi = 1$ we have the maximal deprecation rate $\delta_\beta\delta_0$ with $\delta_\beta \geq 1$. The function δ is then defined as[13]:

$$\delta^X(\xi) = \delta^X(0) + (\delta^X(1) - \delta^X(0))\xi_{W,X}^{a^X} \tag{46}$$

$$= \delta_\alpha^X \delta_0{}^X + (\delta_\beta^X \delta_0{}^X - \delta_\alpha^X \delta_0{}^X) \cdot \xi_{W,X}^{a^X} \tag{47}$$

with

$$a^X = \log \frac{1 - \delta_\alpha^X}{\delta_\beta^X - \delta_\alpha^X} - \log \xi_0^X \tag{48}$$

10.3.2 Expected Demand

Following the ideas described in Section 8.3, a firm does not know the exact demand of the produced good for a given price, and neither the exact inverse function $d(q)$, the result of which is the price p, so that the demand would be q.

Instead the firm has an expected demand function $d_e(q) = \frac{\kappa}{q^\theta}$. The coefficients κ and θ are thereby readjusted in each time step, when the firm gathers information about the real demand. In the current implementation the firm solves an optimization problem $\min_{\theta,\kappa} f(\theta, \kappa)$ to adjust the coefficients.

[13] (48) is the result of solving $\delta(\xi_0) = \delta_0$.

The objective function $f(\theta, \kappa)$ is constructed through the addition of two components. The first component describes the distance between the expected demand $q_{e,t}$ and the real demand $q_{D,t}$, using the knowledge of prices and demand at those prices in the past. The second component describes how fast the firm adjusts its "belief" (in θ and κ) to the newly "learnt" real demand. This is done by calculating and summing the distance between the current and readjusted expected demand for three different prices.

Together, this gives the following objective function f:

$$f(\kappa,\theta) = \sqrt{\frac{\ln^2 \frac{\Gamma(q_t)}{\Delta(p_t)} + \ln^2 \frac{\phi \cdot \Gamma(g_t \cdot q_{t-1})}{\Delta(p_{t-1})}}{1+\phi}} + \psi \sqrt{\sum_{p \in X} \frac{\Xi(p)}{|X|}} \tag{49}$$

where

$$\Delta(p) = \left(\frac{\kappa}{p}\right)^{\frac{1}{\theta}}$$
$$X = \{0.9 \cdot p_t, p_t, 1.1 \cdot p_t\}$$
$$\Xi(p) = \ln^2 \frac{\Gamma\left(\left(\frac{\kappa_{t-1}}{p}\right)^{\frac{1}{\theta_{t-1}}}\right)}{\left(\frac{\kappa}{p}\right)^{\frac{1}{\theta}}}$$
$$\Gamma(q) = (1 + b + \gamma \cdot (g_t - b)) \cdot q$$

Here ϕ determines the weight of point of period $t-1$ and ψ determines the unwillingness of the firm to change the expectation.

The function Γ takes into account that the firm must adjust the expected demand function also to an expected growth of sold quantities in the next period, because (κ_t, θ_t) will be used to determine the firm's production in the next period. Therefore, the firm calculates an expected growth rate by mixing the invariant belief b with the observed GDP growth $\hat{g}_t$.

10.3.3 Production Planning

The `desiredProduction` of a firm results from a ProductionPlanningFunction, which can be different for each firm. Three different kinds of functions have been defined for this purpose. One depends on growth rates, as described in the next section. The second kind optimizes the expected profit of the firm, this is described in Section 10.3.3.2. And the RetrofitFirm has its own ProductionPlanningFuncion, as described in Section 10.3.3.3.

10.3.3.1 Follow Growth Rates

In the first kind of ProductionPlanningFunctions, the firm couples the `desiredProduction` to another growth rate. Three different growth rates can be selected in the current implementation, the `capitalGrowth` as computed in the accounting step (see Section 10.3.7), the `gdpGrowth` or a `fixedDesiredProductionGrowth` which is given as an exogenous input:

$$q^Z_{d,t} = q^Z_{d,t-1} + q^Z_{d,t-1} \cdot \tilde{g}^Z_{t-1} \tag{50}$$

where

$Z \in \{(GenF, Gen),\ (RF, R)\}$

$q^Z_{d,t}$ denotes the desired production of each firm at time t

$\tilde{g}^Z_t$ denotes the `capitalGrowth` rate g^Z_t weighted by the quantity of capital,

or the `gdpGrowth` rate

or some `fixedDesiredProductionGrowth` of each firm at time t

10.3.3.2 Optimize Profit

The second PRODUCTIONPLANNINGFUNCtion depends on a profit optimization process of the firm. Therefore, the firm estimates its production expenses $E_e(q)$ and the demand function $d_e(q)$. Using these functions the firm can calculate its (expected) profit $\pi_e(q) = d_e(q) \cdot q - E_e(q)$.

To determine the `desiredProduction` the profit is “optimized”. Because of the aggregated nature of the agents, this does not mean that the firm maximizes the profit. This would only be a good choice if the firm was to represent a monopoly structure of a sectoral module. Instead the absolute value of the profit is minimized. In the case that the firm can be profitable, this is equal to a profit of zero. This represents an average competitive market of many firms.

$$\min_{q>0} \quad |d_e(q) \cdot q - E_e(q)| \tag{51}$$

The expected demand function has the form

$$d_e(q) = \frac{\kappa}{q^\theta} \tag{52}$$

The production expenses E consist of labour costs and capital costs. The labour costs depend on the hired labour force L and wage, the capital costs depend on the capacity utilization ξ. The firm expects that the wage and goods prices of demanded goods will be the same as in the last period and that the amount of capital is fixed within one period. So the expected expenses functions and therefore also the production depends only on L and ξ:

$$E^W_{e,t}(L, \xi) = w^W_{m,t-1} \cdot L + \sum_X p^X_{m,t-1} \cdot K^{W,X}_{t-1} \cdot \delta^X(\xi^X) \tag{53}$$

where

$W \in \{GenF, RF, CF\},\ X \in \{Gen, G, B\}$

$w^W_{m,t}$ denotes the market wage at time t

$p^X_{m,t}$ denotes the market price of good X at time t

$K^{W,X}_t$ denotes the capital stock of good X of firm W at time t

δ^X denotes the depreciation function of good X

Thus the profit optimization problem of equation (51) for a firm W can be written as

$$\min_{0 \leq L, 0 \leq \xi \leq 1} \quad |q(L,\xi) \cdot d_e(q(L,\xi)) - E^W_{e,t}(L,\xi)| \tag{54}$$

Let $(\hat{L}, \hat{\xi})$ be the solution of the optimization problem. The firm will set the `desiredProduction` as $q^{W,X_W}_{d,t} = q(\hat{L}, \hat{\xi})$, and update its `capitalUtilization` to $\xi^W_t = \hat{\xi}$.

10.3.3.3 Fulfil Contracts

The third kind of production function for the RETROFITFIRM is the following: Because the retrofit market transactions take place before the other good markets transactions, the retrofit firm knows the amount of the retrofit service sold, which can be interpreted as a contract between the retrofit firm and the buyers. The RETROFITFIRM tries to fulfil this contract, therefore `desiredProduction` is set equal to the sum of the sold retrofit service:

$$q^{RF,R}_{d,t} = q^{RF,R}_{m,t} \tag{55}$$

where

$q^{RF,R}_{d,t}$ denotes the desired production of the RETROFITFIRM at time t

$q^{RF,R}_{m,t}$ denotes the quantity of sold retrofit service by the firm at time t

10.3.4 Disposable Income

In most cases, the decision functions of the household that determine the amount of consumption and investment depends on the the `disposableIncome` Y^{disp} of the household.

As long as the income Y is increasing, the disposable income is just the fixed fraction $(1 - s)$ of this income, where s is the savings rate of the household and the income itself is the sum of the loans and the capital income. But in the case that the income decreases, the household tries to keep "its standard of living" and therefore reduces its `monetaryHoldings` m to fill the gap.

$$Y^{\text{disp}}_t = \begin{cases} d & \text{if } d \geq Y^{\text{disp}}_{t-1} \\ d + \min\left(Y^{\text{disp}}_{t-1} - d, m_{t-1}\right) & \text{else} \end{cases} \tag{56}$$

where

$$d = (1 - s) \cdot Y_{t-1}$$
$$Y_t = \sum_g w^g_{m,t} \cdot L^g_t + \sum_g \sum_h r \cdot p^{g,h}_{t-1} \cdot K^{g,h}_{t-1}$$
$$g \in \{\text{GenF, CF, RF}\}$$
$$h \in \{\text{Gen, G, B}\}$$

with $0 \leq s \leq 1$ being the fraction of its income to be saved

and $0 \leq r \leq 1$ the return on capital rate.

10.3.5 Markets

On markets in general, SELLERS and BUYERS enter the market with a supply and demand function, which calculates the supply, demand and price expectation of the current state of the SELLER and BUYER respectively.

Before the start of a negotiation process in a market, all market participants are informed about which market negotiation will come next and have the chance to adjust their internal state. E.g. before the labour market negotiation, the household calculates its maximal labour supply, and its offer function, that will be called by the market repeatedly (because different firms try to hire the household), will return the maximal labour supply reduced by the amount of labour for which contracts with other firms already exists.

An overview of the markets and market actors, including their preparation step is given in Table 7.

Table 7: Market Overview

market	sellers	buyers	pre market activities
retrofit service	RF		calculate price
		CF,GenF,RF,H	retrofit decision
labour	H		labour supply decision
		CF,GenF,RF	production planning
generic good	GenF		calculate price and supply
		GenF,CF,RF	investment decision
		H	desired consumption decision
new buildings	CF		calculate price and supply
		CF,GenF,RF,H	investment decision

CF: Construction firm; GenF: Generic firm; RF: Retrofit firm; H: Household

In the current implementation of the model, a single negotiation process is implemented which follows the first come-first served principle. Calling the method `negotiateFirstComeFirstServed`, the following steps are executed:

The market actors enter the market with demand, supply and a price for this demand/supply, thereby the prices of the SELLER are known by the BUYERS. If the supply price is lower than the demand price, i.e. $p_S \leq p_D$, the transaction price is the price obtained by the price decision function in the considered market. In the current version, the household accepts any price for labour demand and for goods offered by the firms. The amount of goods bought is the minimum of demand and supply. A contract is concluded between the seller and buyer recording the determined amount and price.

10.3.5.1 Retrofit Service Market

Seller The retrofit firm enters the market as a seller of the service to retrofit buildings. It fulfils any demand for retrofit service and sets the `priceForSupply` equal to 1.

Buyers Firms as well as households determine their demand for retrofit service at each period in time. They enter the market as RETROFITINVESTORS and have an amount `Retro-`

`fitInvestor.demand` of how many brown buildings should be retrofitted into green buildings and a `RetrofitInvestor.priceForDemand`.

The `demand` in the current period, $R_{d,t}$, is given by a `retrofitDecisionFunction` which gives back a fixed ratio of the previous period's amount of `capital`, $K_{t-1}^{W,B}$, of brown buildings, i.e. $R_{d,t}^{W} = K_{t-1}^{W,B} \cdot \mu^{W}$, where $W \in \{GenF, RF, CF, H\}$. The share μ^{W} is fixed, but can be different for every buyer. For the household, an alternative `retrofitDecisionFunction` bases the amount of desired retrofitting of buildings on the disposableIncome Y_t^{disp}, so that $R_{d,t}^{H} = \frac{\nu^{R} \cdot Y_t^{\text{disp}}}{p_t^{R}}$.

Currently, only one `retrofitPriceFunction` is implemented, which is such that any price p_t^{R} is accepted, but as shown above, the demand can depend on this price.

10.3.5.2 Labour Market

On the LABOURMARKET, the households acting as APPLICANTs offer some amount of labour. The three different firms, acting as EMPLOYERs, state their labour demand and offered wage. A work contract between an APPLICANT and an EMPLOYER who come to an agreement is constituted by the market and holds for one period.

Seller The household as EMPLOYEE decides the amount of `labourSupply` depending on its `labourSupplyDecisionFunction`. By default, the function is such that `labourSupply` is maximal for any `askedWage`, so the household accepts any given wage.

Buyers To determine the demand for labour, firms calculate their `desiredProduction` by applying a `productionPlanningFunction`. These functions have been given in more detail in 10.3.3. Then the production function of the firm is used to determine the amount of labour needed to fulfil the desired production in the following way:

The `labourDemand` of all firms is computed by solving the production function (see Section 10.3.6) for labour, which gives the following result:

$$L_{D,t}^{W} = \left(\frac{q_{d,t}^{Z_W}}{\left(\frac{\xi^{W,Gen}}{\xi_0^{Gen}} K_{t-1}^{W,Gen}\right)^{\alpha} \left(\frac{\xi^{W,G}}{\xi_0^{G}} K_{t-1}^{W,G} + \frac{\xi^{W,B}}{\xi_0^{B}} K_{t-1}^{W,B}\right)^{\gamma} \left(\eta_{t-1}^{W}\right)^{\beta}} \right)^{\frac{1}{\beta}} \tag{57}$$

where

$W \in \{\text{GenF, CF, RF}\}$

$K_t^{W,X}$ denotes the capital of good $X \in \{Gen, G, B\}$ of firm W

$L_{D,t}^{W}$ denotes the `labourDemand` of firm W

η_t^{W} denotes the `efficiency` of firm W

$\xi^{W,X}$ denotes the `capitalUtilization` of good $X \in \{Gen, G, B\}$ of firm W

ξ_0^{X} denotes the `normalCapitalUtilization` of good $X \in \{Gen, G, B\}$

and $\alpha,\ \beta,\ \gamma$ are given output elasticities of the production function.

All firms start with an individual exogenously given wage $w^W_{D,0}$. Each period the wage gets adjusted to the efficiency improvements η scaled by a constant factor ω:

$$w^W_{D,t} = (1 + \omega \cdot \frac{\eta^W_t - \eta^W_{t-1}}{\eta^W_{t-1}}) w^W_{D,t-1} \tag{58}$$

where

$$W \in \{\text{GenF, CF, RF}\}$$

10.3.5.3 Goods Markets (Generic Good, Green Buildings, Retrofit Services)

In the market configuration of the other three markets we always distinguish between the different types of goods, i.e. GENERICGOOD, GREENBUILDINGS and RETROFIT. The market actors are acting as PRODUCERs, INVESTORs (firms) and CONSUMERs (the household) respectively.

Seller In these markets, the firm that produces the respective good represents the SELLER. The firms decide on their supply and demand as well as on the corresponding price. The `Producer.supply` of generic and real estate firm is given by the `actualProduction` and the `Producer.priceForSupply` is given by some `supplyPriceSetterFunction`. This function depends on the production planning as described in 10.3.3. If the firm W optimizes profit, the price is set to the result of the expected demand function: $p^{Z_W}_S = d^{Z_W}_e(q^{Z_W}_S)$. In all other cases, in the current implementation the price is set to a fixed price.

Buyers The list of agents acting as BUYERs is the same for any of the just mentioned markets: the generic firm, construction firm and real estate firm, investing in the goods, and the household consuming the goods.

The household as consumer plans its `desiredConsumption` using a decision function which determines the consumption of the generic good and the investment into green buildings. There are two alternatives. In the first one, the desired consumption/investment is unlimited, so that the corresponding market is always cleared. The second one distributes the `disposableIncome` Y^{disp} over the different sectors, using the consumption/investment distribution factors ν^{Gen}, ν^G, ν^R with $\nu^{Gen} + \nu^G + \nu^R = 1$. Any given price will be accepted, but the price influences the amount of the demanded of the corresponding sector:

$$C^X_{d,t} = \nu^X \cdot \frac{Y^{\text{disp}}_t}{p^X_t} \tag{59}$$

where

$$X \in \{Gen, G\}$$

The firm's `desiredInvestment` is given by an `investmentDecisionFunction`. Three possible functions have been defined, depending on own production, own capital and overall GDP growth, respectively. For all three cases, the function is given by:

$$I_{d,t}^{W,X} = \begin{cases} K_{t-1}^{W,X} \cdot (g_{t-1}^{W,X} + \delta^X(\xi_t^{W,X})) & \text{if } X \in \{Gen, G\} \\ K_{t-1}^{W,G} \cdot (g_{t-1}^{W,G} + \delta^G(\xi_t^{W,G})) + K_{t-1}^{W,B} \cdot (g_{t-1}^{W,B} + \delta^B(\xi_t^{W,B})) & \text{if } X = G \\ 0 & \text{if } X = B \end{cases} \tag{60}$$

where

$W \in \{GenF, RF, CF\},\ X \in \{Gen, G, B\}$

$I_{d,t}^{W,X}$ denotes the desired investment of firm W in good X at time t

$K_t^{W,X}$ denotes the capital of firm W in good X at time t

$g_t^{W,X}$ denotes the `desiredProductionGrowth` rate of firm W

or the `capitalGrowth` rate of firm W in good X

or the `gdpGrowth` rate at time t

δ^X denotes the depreciation function of the good X,

i.e. the desired investment restores the depreciated capital and adds the amount of growth. Since no brown buildings are produced, the whole demand of new buildings is summed up in green buildings, the demand for brown buildings equals 0, and the capital growth rates of green and brown buildings are calculated as if buildings were a single good:

$$g_t^{W,G} = g_t^{W,B} = \frac{K_t^{W,G} + K_t^{W,B}}{K_{t-1}^{W,G} + K_{t-1}^{W,B}} \tag{61}$$

The `Investor.demand` is given by max(`desiredInvestment`, 0) such that the demand cannot be negative, which would be the case if $g_{t-1}^{W,X_W} < -\delta^X$.

The `Investor.priceForDemand` is given by a `demandPriceSetterFunction` which is such that any price is accepted.

10.3.6 Production

The firms use a Cobb-Douglas function with constant returns to scale. Similar to the approach of e.g. Greenwood/Hercowitz/Huffman 1988, the capacity utilization ξ scales the capital factor(s) of the Cobb-Douglas function. But in the model the exploitation of capital is limited to an upper bound. ξ must be between zero and one, so that a capital factor $K^{(W,X)}$ can be increased only by the factor $\frac{\xi^{W,X}}{\xi_0^X}$.

All in all, the production functions of firms is defined as:

$$q_t^{W,X_W} = \left(\frac{\xi^{W,Gen}}{\xi_0^{Gen}} K_{t-1}^{W,Gen}\right)^{\alpha} \cdot \left(\frac{\xi^{W,G}}{\xi_0^{G}} K_{t-1}^{W,G} + \frac{\xi^{W,B}}{\xi_0^{B}} K_{t-1}^{W,B}\right)^{\gamma} \cdot \left(L_{m,t}^{\mathrm{W}} \cdot \eta_{t-1}^{W}\right)^{\beta} \tag{62}$$

where

$(W, X_W) \in \{(GenF, Gen), (CF, G), (RF, R)\}$
q_t^{W,X_W} denotes the production of good X_W of the firm W at time t
$K_t^{W,X}$ denotes the amount of the capital of good X of firm W
$L_{m,t}^{W}$ denotes the amount of `marketLabour` of the firm W (resp. RF)
$\xi^{W,X}$ denotes the `capitalUtilization` of good $X \in \{Gen, G, B\}$ of firm W
ξ_0^X denotes the `normalCapitalUtilization` of good $X \in \{Gen, G, B\}$
η_t^W denotes the `efficiency` of the firm W (resp. RF)
and $\alpha,\ \beta,\ \gamma$ are the output elasticities.

10.3.7 Accounting

All agents, that is, the different firms and the household, carry out an accounting step, specified differently for the different agents. Part of this accounting step is the depreciation of owned capital, which depends on the capacity utilization.

10.3.7.1 Firms

The new amount of the `capital`, the `capitalGrowth`, the `buildingsGrowth` and the `efficiency` are computed. For capital, the following holds:

$$K_t^{W,X} = (1 - \delta^X(\xi_t^{W,X})) \cdot K_{t-1}^{W,X} + I_t^{W,X} + R_t^{W,X} \tag{63}$$

where

$K_t^{W,X}$ denotes the amount of the capital of good X of firm W at time step t
$I_t^{W,X}$ denotes the amount of good X of firm W bought in the resp. good market
R_t^W denotes the amount of retrofitted buildings of firm W at time t
$R_t^{W,G} = -R_t^{W,B} = R_t^W$
$R_t^{W,Gen} = R_t^{W,R} = 0$
$\xi_t^{W,X}$ denotes the capacity utilization of good X of firm W at time step t
δ^X denotes the depreciation function of good X, as described in 10.3.1.

Firms compute their `profit` by subtracting the `productionsCost` from the `earned-TurnOver`. The `earnedTurnover` is obtained from the goods market by multiplying the amount of the goods sold with their price.

The efficiency of a firm is adjusted according to the growth of capital:

$$\eta_t^W = (1 + g_t^{W,X_W}) \cdot \eta_{t-1}^W \tag{64}$$

where

g_t^{W,X_W} denotes the growth rate of capital of good X_W produced by firm W owned by this firm.

The monetaryHoldings of a firm are updated in the following way: the wageBill and the investmentTurnover are subtracted from the monetary holdings of the last period lP.monetaryHoldings and the just computed earnedTurnover is added. The overall turnover of the goods bought as INVESTOR and RETROFITORDERER, is the investmentTurnover. Also the expectedDemand function is updated as described in 10.3.2, using as new information the marketTransactionPrice $p_S^{Z_W}$ and amount of goods sold $q_m^{Z_W}$.

10.3.7.2 Household

The household updates its capital, actualConsumption, and monetaryHoldings in the accounting step.

It consumes the GENERICGOOD. The capital updating function is the same as described for the firm above (with $X \in \{G, B, R\}$).

The actualConsumption is given by the amount of the genericGood bought by the household on the goods market.

The monetaryHoldings are computed similarly to those of the firms: The wageBill is added to last period's monetaryHoldings and the overallTurnover of the goods bought, also in the role of RETROFITORDERER, is subtracted.

10.3.8 Emissions

CO_2 emissions are considered to be caused by the capital stock. Each type of capital has its own emission factor ρ^X. Section 11.2.2.3 describes how this factor can be derived using as an example data from Germany. The efficiency improvements for the generic good and green buildings are exogenous given by a constant rate ζ. All in all, emissions can be calculated as:

$$\Upsilon_t = v \cdot \rho^G \cdot K_t^{H,G} + \sum_g \left(v \cdot \rho^{Gen} \cdot K_t^{g,Gen} + v \cdot \rho^G \cdot K_t^{g,G} + \rho^B \cdot K_t^{g,B} \right) \tag{65}$$

where

$v = (1 - \zeta)^t$

$g \in \{GenF, BF, RF\}$

11

Data and Calibration

In contrast to macro-module A (MM-A) described in 8.4.1, to goal is to use the implementation of macro-module S (MM-S) for policy simulations. This implies that an implementation instance of MM-S should be based on empirical input data and should be able to reproduce stylized facts of the economy. To archive this, it is necessary to calibrate the model. How this is done in MM-S is described in Section 11.1.

Section 11.2 documents the corresponding empirical input and gives a technical description about the file format used for reading the input into the model.

11.1 Calibration of Macro-Module S

In case that the firm optimises its profit, it is important that the outcome of this optimisation process matches the empirical data given as input. How this can be archived is shown and discussed in this section.

Therefore we start with a recap of a subset of formulas that are needed for this task, and then explain which values must equal empirical data. Also some variables, which where fixed values in previous versions of corresponding formulas, are now listed as function parameters. This should make aware about the fact that those parameters are set as an outcome of the calibration process.

Table 8 lists the variables, values, and functions used in these formulas, grouped into different categories:

Table 8: Calibration Variables, Values and Functions

notation	meaning	see
	functions	
ρ	production function	(66)
D	expected demand function	(67)
π	profit	(68)
	empirical values	
w_0	wage	
K_0	capital	
m_0^F	firms monetary holdings	
m_0^H	households monetary holdings	
r	return on capital	
v_0	empirical data for production	
g_0	growth rate of first period	
	literature values	
α, β	output elasticities	
δ	depreciation	
	determined variables	
p	price	(67)
$I^{(D)}$	investment (demand)	(69)
$C^{(D)}$	consumption (demand)	(70)
L	labour	(71)
	free variables	
η	efficiency	
κ, θ	expected demand coefficients	

- *empirical values* are values that are derived from empirical data.
- *literature values* are values that can not be measured directly and therefore only estimate using proxies.
- *determined variables* can be derived from other entities, e.g. as results from a function.

- *free variables* are the variables that can be freely adjusted so that the outcome of the calibration process matches given constraints.

11.1.1 Recap

$$
\begin{aligned}
\rho(L,\eta) &= K_0^{\alpha}(\eta L)^{\beta} && (66)\\
(p =)D\,(L,\eta,\kappa,\theta) &= \frac{\kappa}{\left(K_0^{\alpha}(\eta L)^{\beta}\right)^{\theta}} && (67)\\
\pi(L,w,\eta,\kappa,\theta) &= \rho(L,\eta)\cdot p - w\cdot L - p\cdot K_0\cdot\delta - (p\cdot K_0 + m_0^F)\cdot r && (68)\\
I^D &= K_0\cdot(g_0+\delta) && (69)\\
C^D &= \frac{m_0^H}{p} && (70)
\end{aligned}
$$

L is determined by an optimization of the profit π:

$$\min_{0\leq L\leq L_{max}} |\pi(L,w,\eta,\kappa,\theta)| \tag{71}$$

There are two empirical values that must be fit after the profit optimization process: The sum of the household's consumption and the firm's investment must be greater or equal than $q_t = \rho(L,\eta)$[14], and the value of the production v_0 must be approx equal to production amount multiplied with the price derived from the expected demand function:

$$
\begin{aligned}
\rho(L,\eta) &\leq C^D + I^D && (72)\\
(1+g_0)v_0 &\approx \rho(L,\eta)\cdot D(L,\eta,\kappa,\theta) && (73)
\end{aligned}
$$

It's easy to see that (72) requires that $m^H \geq p\cdot(\rho(L,\eta) - K_0\cdot(g_0+r))$

11.1.2 As an Optimization Problem

To solve (72) and (73) at the same time, we can combine both into a single optimization problem:

$$
\begin{aligned}
\min_{\eta,\kappa,\theta,w} \quad & \Psi + \Phi && (74)\\
\text{s.t.} \quad & && \\
& L = \arg\min_{L} |\pi(L,w,\eta,\kappa,\theta)| && (75)\\
& \Psi = \log^2\left(\frac{\rho(L,\eta)D(L,\eta,\kappa,\theta)}{(1+g_{t_0})v_0}\right) && (76)\\
& \Phi = \log^2\left(\frac{\min\{C^D + I^D, \rho(L,\eta)\}}{\rho(L,\eta)}\right) && (77)\\
& m^H \geq p\cdot(\rho(L,\eta) - K(g_0+r)) && (78)
\end{aligned}
$$

If a solution exists, the resulting $\Psi + \Phi$ should be approx 0.

[14] In the case that it is greater this just means that the household will have a higher demand then the firm can fulfill.

11.1.3 Algebraic

As already mentioned in Footnote 8 on Page 56, in MM-S all prices are set to 1. From this follows that η can be derived from (66) - (73):

$$p = 1 \quad \Rightarrow \quad q = v_0 \cdot (1 + g_0) = \kappa^{\frac{1}{\theta}} \tag{79}$$

$$0 = q - w \cdot L - K \cdot \delta - (K + m) \cdot d \quad \Rightarrow \quad L = \frac{q - K \cdot \delta - (K + m) \cdot d}{w} \tag{80}$$

$$K^{\alpha} \cdot (\eta \cdot L)^{\beta} = q = \quad \Rightarrow \quad L = \left(\frac{q}{K^{\alpha}}\right)^{\frac{1}{\beta}} \cdot \eta^{-1} \tag{81}$$

$$\Rightarrow \quad \eta = \frac{\left(\frac{q}{K^{\alpha}}\right)^{\frac{1}{\beta}} \cdot w}{q - K \cdot \delta - (K + m) \cdot d} \tag{82}$$

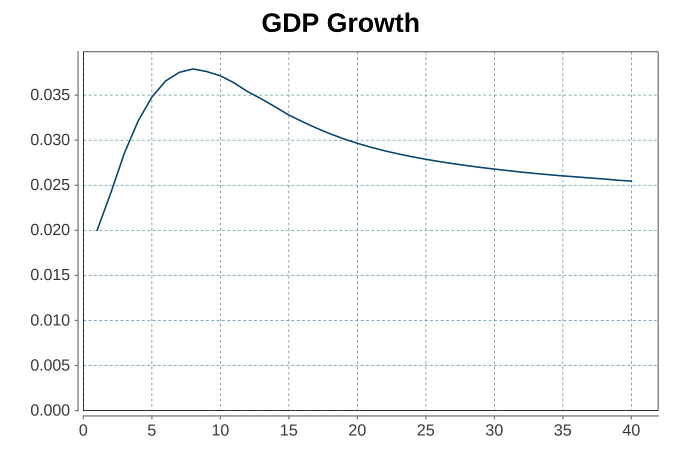
(79) can be used to calculate κ by setting θ to a value between 0 and 1.[15]

$$\kappa = q^{\theta} \tag{83}$$

11.1.4 Results

Both solution approaches have the same results, an example is shown in Figure 33. In this example the initial values are set in a way that they should result in a constant GDP growth of 2%. This is not archived perfectly, the simulation run starts with a hump in the GDP growth before it converges back to 2%. But it is easy to see a big difference to the GDP growth rates shown in Section 9.2, which are created with MM-A, where no calibration is executed.

Figure 33: Calibration results



[15] From our current experience we got the impression that values between 0.5 and 0.7 are a good choice.

11.2 The Default Data File for Macro-Module S with Simple Buildings Module

MM-S is developed and is going to be used together with a data file, meaning that the module user can set the conditions for simulation runs. It can serve as a template for providing empirical input data to the module and allows to input different empirical data to initialise the module so that it can represent any given economic system at a certain point in time.

For now we only use one data point (most recent) to initialise the model and then run future scenarios. At a later stage we can use earlier data points for initialisation and then run scenarios and compare them with the data from that particular year.

The format of the data file is described in Section 11.2.1. To initialise the model we need macro-economic and sector-specific data as specified in Section 11.2.2. Since the first simulations using STOEMSys focus on the economic effects of energy efficiency improvements in buildings, the sector-specific data focus on the construction sector as well as the structure of the buildings stock, and will serve as an example for the integration of further sectors later on.

11.2.1 File Format

The data file is a comma-separated value (csv) file, which is a plain text file that uses commas (and line endings) as a separator between different entities. The whole data file can be interpreted as a table where the number of rows is equal to the number of lines of the file, and the number of columns is equals to max(1 + number of commas in row). Each row (line) can be empty or must have one of following elements:

- Comments
- Information about the following variable values
- The previously described variable values themselves

11.2.1.1 Comments

Comments begin with a // in the first column, the following text of the first column and also the following columns of the row can be used arbitrarily, as they are not interpreted by the computer but included just for the reader. An example:
`//this is just a comment.`

11.2.1.2 Information About the Following Variable Values

The first column describes the type of the variable whereby the following types are supported: `Int`, `IntVector`, `Float`, `FloatVector`, `FloatMatrix`, `FloatCuboid`, `Boolean` and `FuncSelector`.

The second column contains the name of the class, as seen in the source code documentation (the InitValue classes), the third column the name of the variable in the source code, and the fourth column the name of the variable as shown in the user interface. E.g. the complete row that describes the investment decision function for the retrofit sector would be `FuncSelector,RetrofitInitValues,idf,"Investment Decision Function"`

The `FloatMatrix` and `FloatCuboid` types can be parameterized in the fifth and sixth column, the details are described below.

11.2.1.3 The Previously Described Variable Values Themselves

The format of the row(s) after a row with variable information depends on the variable type. Beside for matrices and cuboids only one line is used for the values:

- `Int/Float`: The row contains only a single value, which will be interpreted as an integer or float value.
- `Boolean`: Booleans are stored as text, the valid keywords are `false` and `true`.
- `IntVector/FloatVector`: By default a vector is created with the same size as the number of columns used in the row. The value of the first column will be read as the first element of the vector, the value of the second column as the second element etc.
- `FloatMatrix`: By default, a quadratic matrix is created with the same size as the number of columns used in the first row. The columns of the matrix are the columns of the csv file, the rows of the matrix are the rows that follow the variable information row. In the case that the matrix is not quadratic, the number of rows must be given in the fifth column of the variable description row.
- `FloatCuboid`: This is a "3 dimensional matrix", expressed in Scala as:
  `Array[Array[Array[Double]]])`. The values are written in form of n-matrices, where n is the size of the first dimension.
  For example, an `Array.fill(2)(Array.fill(3)(Array.ofDim(4)))` would have the following layout:

  ```
  111 112 113 114
  121 122 123 124
  131 132 133 134
  211 212 213 214
  221 222 223 224
  231 232 233 234
  ```

  In the case that not all dimensions have the same size, the fifth and sixth columns of the variable description row determine the size of the first and second dimension.
- `FuncSelector`: The row contains the name of the decision function as plain text.

11.2.2 Default Data Description

This section serves to describe the data used to initialize MM-S as well as the buildings module. All input variables used for the macro-module and sectoral module are described below.

For the macro-module the default data file was generated using empirical data. Since the project focuses on climate and energy policy in Germany, we use data from the German

Bureau of Statistics (Destatis) if not indicated otherwise. Monetary values are Euros in current prices. Base year for all data is 2010.

The data used in the sectoral module is just, if at all, a rough estimation. As the module is meant to be replaced by a detailed sectoral module, this estimation seemed good enough for the "dummy" buildings module.

The data file can be found in Table 9 and can be understood in the following way:

11.2.2.1 Capital

The MM-S & BM model of the STOEM-Sys distinguishes between four kinds of capital (see Section 10 for details):

- "green" capital are buildings with high energy efficiency
- "brown" capital are buildings with low energy efficiency
- all other types of capital are called "generic" capital

The exact distinction between green and brown buildings is explained in detail in Section 5 of Jaeger et al. (2013). The buildings stock of each of the four agents is divided into brown and green buildings according to the overall ratio 3:1. For simplification, we do not assume that different agents have different shares of green and brown buildings. Furthermore, we treat commercial and residential buildings the same and aggregate them. However, these assumptions can be refined at a later stage by integrating expert knowledge.

Generic capital stock combines all other types of capital, such as inventory, tools, machinery and equipment.

Table 9: Default data

Input variable	Values	Unit
Generic Firm		
Capital generic	1017	€bn
Capital green	1370	€bn
Capital brown	4110	€bn
Production	2000	€bn
Construction Firm		
Capital generic	200	€bn
Capital green	50	€bn
Capital brown	150	€bn
Production (green)	200	€bn
Retrofit Firm		
Capital generic	400	€bn
Capital green	100	€bn
Capital brown	300	€bn
Production	400	€bn
Generic Households		
Capital green	1600	€bn
Capital brown	4800	€bn
Depreciation		
generic capital	20	%
buildings capital	2.5	%
real estate capital	100	%
Emissions		
Generic capital	654.3	kg CO_2/€ of capital
Green building capital	26.7	kg CO_2/€ of capital
Brown building capital	53.7	kg CO_2/€ of capital

Source: destatis and own estimations (for the Construction & Retrofit Firm).

Numbers for depreciation also follow the statistics results for the sum of all remaining sectors. Compared to the 2.5% for buildings, we find a much higher deprecation for generic capital of 20%. For the depreciation rate of buildings, the average rates for the total building capital are used. They are chosen match the statistics given in a weighted average.

11.2.2.2 Production

Production is measured as gross value added. Numbers for real estate and construction are taken directly from the statistics. The generic sector production contains all gross value added from the remaining sectors in the economy and contributes about 90% of the total production. We extended the construction and retrofit sector, which can be interpreted as including more downstream industries providing intermediate products used for retrofitting. This is done due to the fact that the model does not yet contain intermediate goods but the production of a sector is understood as value added, not as its turnover.

11.2.2.3 Emissions

CO_2 emissions are considered to be caused by capital goods in the current implementation. Therefore emission factors are listed in kg CO_2 per Euro of capital. A change in the composition of the total capital stock can decrease or increase the emissions. We use a linear model, which calculates the emissions with a constant factor per unit of each type of capital. Approximately 37% of total CO_2 emissions in Germany arise from buildings, mainly for heating and electricity. These need to be assigned to green and brown buildings, taking into account the size of capital stock as well as the emission intensity. The emission factors for each type of building capital (brown and green) are calculated under the assumption that one unit of brown building capital causes two times the amount of CO_2 in comparison to one unit green capital. The ratio 2:1 is based on the energy use per m^2 for old and new buildings, as specified in Section 5 of Jaeger et al. (2013). The emission factor for generic capital is calculated by dividing the remaining emissions by the amount of generic capital stock.

Part II
Supplementary Project Work

12 Stakeholder Dialogues

The development of STOEMSys modules was based on a continuous process of interactions and dialogues with experts on sector specific models for assessing climate policy measures, experts on new economic thinking and complexity economics, as well as potential model users. The dialogues took place in form of workshops, conferences and bilateral meetings. Some of these meetings have already been documented in earlier project reports (Jaeger et al. 2013; Jaeger et al. 2014); for completeness, the whole dialogue process is summarized in this final report. Programmes of all events and the presentations by GCF staff, showing the respective progress made regarding the modelling work, can be found in Annex A.

It was an explicit aim of the dialogues to combine current economic discussions with environmental discussions, in order to identify win-win opportunities. Discussing real-world challenges at macroeconomic level, such as the Eurozone crisis, and at sectoral level, such as the challenge of retrofitting the building stock or transforming the energy sector, proved to be a useful approach for two reasons: 1) these specific problems provide inspiration and guidance for creating and developing (theoretical) insights 2) the focus on the Eurozone crisis increases the relevance of the project's research for new economic thinkers who are not particularly interested in the ecological sustainability dimension. Hence, we were able to attract excellent researchers to the workshops and conferences.

12.1 Workshops

All three workshops focused on modelling the transformation to an economy with reduced energy demand, an energy system based on renewable energies and the required system integration.

12.1.1 Workshop I

The first workshop was held in June 2012 at Mercator ProjektZentrum Berlin. The topic of the workshop was "Germany and Europe: Towards a New Growth Path? – A new Franco-German Dialog and European Energy Transmission Networks". Among the participants were German and French economists, mathematicians, energy policy and grid experts with research focus on both or either of the topics.

The topic was chosen due to the election outcome in France, which triggered a political debate about the European Union, at the time. This was taken as a starting point, to ask whether a shift to a green growth path, and the necessary transformations of electricity grids throughout Europe, could facilitate European integration in the light of the Eurozone crisis.

The first session focused on the economic situation of the European Union, with discussions about a fiscal union, Eurobonds, project bonds and the stabilization of the financial system. An important point made was that debt should be distinguished between debt that helps the productive part of the economy and non-productive debt.

The second session focused on the role of energy transmission networks in Germany and Europe. The main topics discussed were the challenges that arise from an energy system with a large share of renewable energy and the long planning horizon for power grids. An important point made was that the restructuring of the energy market and the energy grid should be regarded as a common task working towards further European integration, which can trigger productive investments and lead to higher economic growth. Furthermore, creating local benefits is an important factor for acceptance. The grid renewal can be used as an example for using new European financing schemes, such as project bonds.

12.1.2 Workshop II

The second workshop was held in December 2012 at the Mercator ProjektZentrum Berlin with the title “Germany and Europe: Towards a New Growth Path? – “Energy sector transition - German madness or an opportunity for growth?”.

The topic of the workshop was the German energy transformation (“Energiewende") and its political and economic implications for other (European) countries. It was held before the background of intense German debate about rising electricity prices due to increased shares of renewable energy in the power system, and addressed the question whether Germany is able to show that the energy transformation can pay off in an economic sense of increasing employment and growth at a short to medium time horizon.

This workshop included many inspiring presentations and discussions looking at the micro-level by analyzing the electricity sector (at the German, Dutch, European and international level) and looking at the macro-level by assessing cross-sectoral effects as well as macroeconomic impacts.

The first part of the workshop centered around the challenge that striving towards an 80% share of renewables by 2050 is more complex than often thought. It will require massive changes in technology and infrastructure related to production, storage, grid and consumption, as well as associated transformations of governance structures and the market mechanisms themselves. The second part of the workshop dealt with the question whether green growth can offer the opportunity to reach a superior equilibrium in economic, social and environmental terms. It was concluded that a transition to a new growth path entails more than an energy sector transition alone and needs to be put into a broader perspective, which is a challenge from a modelling perspective.

12.1.3 Workshop III

The third workshop, held on July 14, 2014 was part of a conference with the title: “Green Business Models and Green Growth – A New Vision for Europe?”. The workshop related to this project had the title “Green Growth Strategies” and focused on discussing opportunities for win-win strategies of climate policy.

The first session focused on discussing different modeling approaches used in climate policy, especially their assumptions regarding the state of the economy (in equilibrium, out-of-equilibrium or multiple equilibria) and the subsequent strengths and limitations of different models.

The aim of the second session was to discuss a new strand of models, agent-based models (ABMs). The presentations focused on economic and financial market issues. A point of discussion was that most models used for climate policy assume that financial and capital markets work perfectly and that banks are just intermediaries. However, the representation of banking and finance in climate economic models needs to be improved, if one wants to take into account the current economic situation in the EU.

The third session focused on the energy efficiency potential. One question discussed was how the equilibrium approach fits with the abatement cost curves, which show that there are investment opportunities at negative cost. Reasons discussed were the heterogeneous structure of the building stock, a lack of information, as well as a low share of energy costs compared to total costs for most firms. A second question discussed was whether regulation is the only way to increase energy efficiency investments. Other possibilities, such as an obligation scheme for utility companies, were discussed.

12.2 Conferences

12.2.1 Meeting at the Second Open Global Systems Science Conference

One important stakeholder meeting was the “Second Open Global Systems Science Conference” from June 10 to 12, 2013 in Brussels, Belgium. The conference was organized in cooperation with several European research projects within the research network “Global Systems Science” to ensure a high quality of international experts. A workshop on June 12 on “Climate Policy” chaired by Prof. Carlo Jaeger was especially dedicated to presenting the prototype of the macromodule, combined with a simple buildings module, to an international and interdisciplinary audience.

The main topic of the workshop were the challenges in climate policy. Special attention was drawn to the differences at the national level and international level while keeping in mind the tensions between climate and economic policies. Concerning national/EU level policies, the discussion centred around energy efficiency in the buildings sector. Important aspects under discussion were investment requirements and related macroeconomic and cross-sectoral effects of policies in this area.

The prototype of the model, including the details of the building sector, was presented by Franziska Schütze (Global Climate Forum) with the title “German Green Growth Model – macroeconomic implications of sector specific climate policies”. The second presentation was given by Oliver Rapf (Buildings Performance Institute Europe) on “Policy challenges in the building sector”, which provided very detailed insight into the building sector in the entire EU. An important outcome of the discussion was that the integration of top-down and bottom-up models and approaches is essential for making progress in climate policy, hence approving the approach of this project. From the discussion it became clear that the building sector itself and the actors involved are very heterogeneous and policies have to take this into account. Furthermore, very different policies are implemented in different European countries. Also, specific skills and therefore training needs to be improved. There is a need for a coordinated training program in the building sector all over the EU. The employment effect is estimated to be 0.2 - 0.8 million jobs per million Euro invested. It was mentioned that most policy makers are not aware of the overlap of energy efficiency measures and, for example, employment effects.

The second part of the discussion was concerned with international climate negotiations and insights from game theoretical approaches, with a presentation by Jobst Heitzig (Potsdam

Institute for Climate Change Research) on “dynamic models of rational or boundedly rational climate coalition formation on networks”. The main result is that a grand coalition will form, depending on the assumptions for the specific utility functions of different countries. All countries will cooperate eventually. The presentation was followed by a discussion on the assumptions of the utility function, e.g. whether the future benefit from a climate deal will be larger than 0 for each country and whether a country’s contribution will always come at a cost (or mitigation could also benefit a country) and which implications this would have in terms of outcomes.

The subsequent discussion was dedicated to the synergies between national sector-specific policies and international policies and their contribution to a transformation to a low-carbon economy, separately or jointly. Most participants shared the view that the 2015 climate negotiations will be decisive. However, there needs to be a change in sentiment from burden sharing to opportunity sharing to convince countries to agree on ambitious targets.

12.2.2 Meeting at the Third Open Global Systems Science Conference

The second conference was again organized in cooperation with the research network “Global Systems Science” to ensure an exposure to international experts. This time the conference was organized in three locations at the same time (Phoenix, Beijing and Brussels) under the header "Third Open Global Systems Science Conference: Unpacking Green Growth. The Beijing part of the conference took place on 7-8 October 2014 in Beijing, and was especially dedicated to presenting a preliminary version of the model to an interdisciplinary audience.

Participants of the meeting included primarily climate change experts and scientists from Beijing Normal University and from the EU, as well as a representative of the OECD. Experts and politicians based in Brussels, Belgium and Phoenix, Arizona participated via video conferencing.

The conference focused on how to best model how climate change and climate policy will affect economic flows. Agent-based modelling was discussed as one important method which can be used when there are many uncertainties involved.

Agent-based models were discussed in the Chinese context by Saini Yang (State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University) and Wenxu Wang, School of Systems Science, Beijing Normal University. Insights regarding air pollution disasters and related economic losses were provided by Kaicun Wang (College of Global Change and Earth System Science, Beijing Normal University), Lianyou Liu (Academy of Disaster Reduction and Emergency Management, Beijing Normal University), and Yanli Lyu (State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University).

Franziska Schütze presented the general modular structure and the main components of the models developed in this project. Focus of the presentation was the need for larger investments in climate mitigation, especially in energy efficiency and how these can be financed. This was discussed in the context of industrialized but also developing and emerging economies. Resulting from this, the question was what is required in terms of modelling to address these questions. The approach chosen for model developed for this project, is to start from an Arrow-Debreu General Equilibrium setting, but to move towards an Agent-based approach where excess supply and demand is possible due to expectation dynamics and the introduction of fiat money.

Sarah Wolf discussed whether Green Growth can be a solution to the problem of climate change on the one hand and the Eurozone crisis on the other hand. Focus of the presentation was the need to challenge the single equilibrium approach of different computational economic models and the need to analyse multiple equilibria. This is necessary to address the question how the multitude of heterogeneous agents in the economic system can re-coordinate so as to move from the current fossil fuel based economy to a green economy.

Gesine Steudle presented the price dynamics of models developed in this project. Starting from general equilibrium theory where prices are determined by solving equations to find an equilibrium point, from the Sonnenschein-Mantel-Debreu theorem it can be derived that multiple equilibria are possible. The price dynamics implemented in STOEMSys models were presented as one way to describe the transition dynamics between different equilibria, which is still an unsolved question.

The intercontinental plenary “Reframing the global climate-growth debate: from burden sharing to opportunity creation” was live-streamed from Brussels. John Ashton (former Special Representative for Climate Change) directed the main presentation and highlighted the importance of private-public partnerships in development of robust and meaningful green growth strategies. In the discussion that followed, the significance of considering mainstreaming adaptation in policies aimed towards green growth across sectors was noted.

Subsequently, the interest for further collaboration between GCF, the OECD and DRC was agreed. Potential joint work would focus on indicators for green growth and mainstreaming of climate policies, which means to better embed climate policies in other policies (growth, employment, health, etc.).

12.3 Bilateral Meetings

Concerning stakeholder dialogues with modellers from specific sectors, it was not considered expedient to bring different kinds of modellers together for detailed discussions of the respective models. Therefore, several smaller bilateral meetings were organized instead.

One meeting was held with modellers from DLR (German Aerospace Center, Institute for technical thermodynamics, system analysis and technology assessment) in Berlin. This group has developed a bottom-up agent-based energy model, called AMIRIS, which can simulate the influences of different regulatory frameworks on involved actors regarding the market integration of renewable energy. The aim of the meeting was to understand each others models and to discuss possibilities to couple them.

Another meeting was held with researchers from Beijing Normal University (BNU). This meeting concentrated on the problem of price dynamics in macroeconomic models. This discussion was decisive for the introduction of the price dynamics used in STOEMSys, and was further developed after the meeting.

As a result of the 3rd Workshop, a possibility for cooperation with ECOFYS emerged. While the project comes to a close, the excercise of complementing a STOEMSys macromodule with the Built Environment Analysis Model – BEAM[2] shall be pursued beyond the project. For details, see Section 9.3.2.

13

Sector Analysis: Investment needs and economic impact

The aim of the model under development is to offer useful insights for policy making. Therefore, the scenarios should be oriented towards the political discussions. Germany has set itself an emission reduction target of 40% by 2020. The German approach to reach this goal cannot be investigated in isolation from the efforts of the EU. At the European level, the new target for 2030 is a 40% GHG emission reduction.

This research project aims at improving the integration of bottom-up insight into top-down macroeconomic modelling, by applying a modular structure. Emission reductions are distributed rather unevenly between sectors and actors (see also Section 6.2). In order to assess how top-down goals can be achieved, it is necessary to investigate the current as well as potential emission reductions at sector level, focusing on the sectors with the largest shares of emissions.

This task has been subcontracted to *SEPAN research* within the project. This section will summarize the main findings of the report Meißner/Krause/Jaeger (2013) and highlight the important findings with regards to the model under development. The full report can be found in (Annex B).

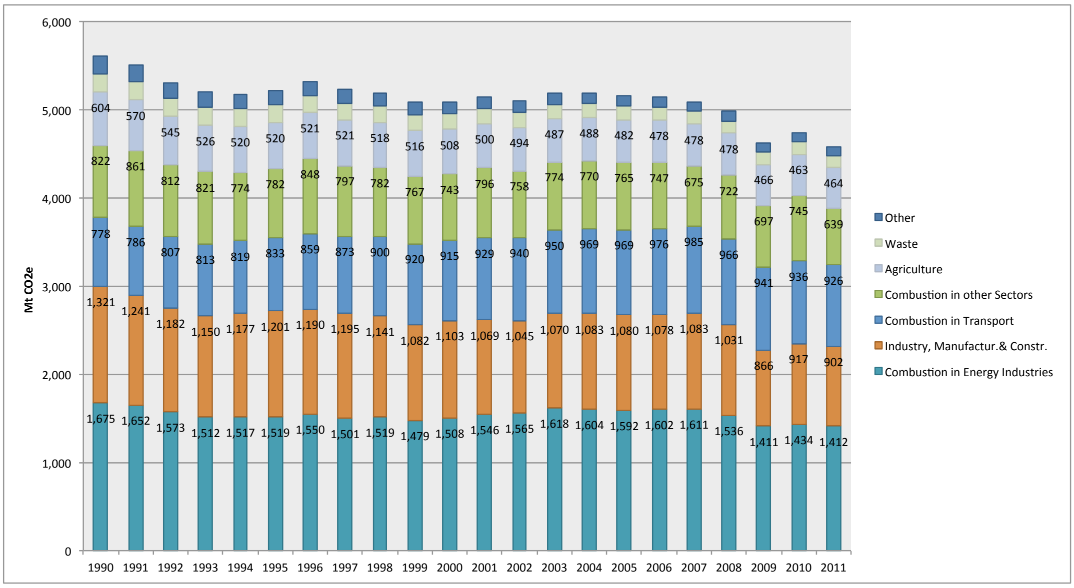
13.1 General Findings

Since the energy use of an economy is very important for emission reduction efforts, energy use by sector as well as GHG emissions by sector have been investigated in the study. To avoid confusion, this summary will mainly report GHG emissions, and energy use only when necessary. Since we are taking the EU targets as a reference point we are referring to EU data. If not stated otherwise, numbers are taken from Eurostat and are based on data from the European Energy Agency. Estimates are adopted from Meißner/Krause/Jaeger (2013) if not stated otherwise.

The data shows that there are large differences between sectors regarding the development of GHG emissions. With 34% the industry sector showed the largest decline in GHG emissions from 1990 until 2011. The agricultural sector and other sectors including households decreased emissions by slightly more than 20%. The emissions of the energy sector decreased by about 15%. The transport sector, however, increased its GHG emissions by about 20% in the same period.

The financial crisis of 2008/09 had the largest influence on GHG emissions by industry, with a decrease of about 15-20% (and an increase of about 5% in the subsequent years). The effects on energy sector emissions and transport emissions were lower, with 10% and 5% respectively. However, there was no noticeable effect on the emissions of the agricultural and other sectors (including households). This is an interesting fact to be considered when modelling the effect of an economic downturn on emissions. The development of GHG emissions, including the effect of the crisis, is visible in Figure 34.

Figure 34: GHG Emissions for EU28 in Mt CO2 equivalent



Source: eurostat(2014).

13.2 Energy Sector

The EU energy sector has the highest emissions, with 1412 $MtCO_2e$ in 2011, and the highest potential for reductions of carbon intensity (by substituting with renewable energy) and increasing the energy efficiency of different technologies (by retrofitting existing power plants). According to Meißner/Krause/Jaeger (2013) GHG emissions could be reduced to around 517 $MtCO_2e$ in 2030, with a share of renewable energy of 40%.

The relative prices of fossil fuels and renewable energy (and expected future prices) are decisive for investment patterns. Therefore, power production costs by technology play an important role. The power production costs from fossil fuels according to Nitsch (2007) will increase from 3-5 ct/kWh in 2010 to 3.5-7 ct/kWh in 2030. However, there is a high level of uncertainty about the development of world market prices for fossil fuels, which are a main driver of power production costs. In constrast, the power production costs of renewable energy mainly depend on technological development and are therefore projected to decrease until 2030. The learning curve effect has been estimated by several studies. BDU (2012) predicts the annual price decrease to be 4% for wind and ISE (2013) expects an annual price decrease of 15% for solar PV.

Investments in new fossil power plants are still taking place, less so in Germany and Europe, but more extensively in the rest of the world. However, these were not taken into account by Meißner/Krause/Jaeger (2013) because the main question was how much investment will be needed to build the required capacity of renewable energy. They estimate required investments in renewable energy to be around €255 bn between 2012 and 2030 for wind power, €53 bn for biomass, €138 bn for solar PV. Additionally, investments in new infrastructure (grids) of approximately €200 bn and another €80 bn for storage capacity will be necessary. This will result in overall additional investment needs of around €726 bn from 2012-2030.

A required change in market design is becoming an increasingly important issue for the transformation of the energy system. A new market design would have to address the following challenges:

- a shift from operation-intensive fossil fuels to capital-intensive renewables,
- offering investment incentives for renewable energies and highly flexible fossil power plants as well as energy storage,
- offering incentives for higher flexibility of supply and demand to accommodate the intermittent renewables,
- mastering the increasing decentralization of the energy system.

Furthermore, the development of the electricity grid needs to be coordinated at European level to increase efficiency.

13.3 Households

Emissions from households (from energy combustion, not electricity) have decreased from 1990 to 2011 by 21% (from 517 to 409 $MtCO_2e$). The emission reduction potential is estimated at around 42% (down to 236 $MtCO_2e$) in a 50% overall reduction scenario.

End energy use over the same period has stayed at around 273 Mtoe. However, there was a shift towards a higher share of electricity. The demand for electricity has increased from 52 to 69 Mtoe, and the share of other primary energy use (mainly for heating) has decreased from 221 to 204 Mtoe. GHG emissions from electricity use are allocated to the energy sector and are therefore not further considered here.

Regarding energy efficiency, it is assumed by Meißner/Krause/Jaeger (2013) that the carbon intensity for households can be reduced from 2.0 tCO_2/toe in 2011 to 1.7 tCO_2/toe by 2030 (2.3 tCO_2/toe in 1990). One of the difficulties is that the existing building stock is heterogeneous and therefore the emission reduction potential is very different depending on the age and type of buildings. Countries with more than 70% of houses built before 1975 are Belgium, Bulgaria, Germany, Denmark, Italy, Romania and the UK. Countries with more than 70% of single family use are Belgium, Ireland, Iceland, Luxembourg, Malta, the Netherlands, Norway and the UK. However, energy use for heating is not necessarily highest in these countries (Lechtenböhmer/Schüring 2009). The countries with the highest energy demand for heating are Latvia, Finland and Estonia with 170-200 kWh/m2a, and Poland, Czech Republic, Romania, Slovakia, Austria, Germany and Hungary with 150-170 kWh/m2a. The EU average is at 130 kWh/m2a (EEA 2013). For a 50% reduction scenario, the retrofit rate needs to increase substantially, from currently around 1% to 3-4% per year.

In the report for this project, it was assumed that the retrofit rate can be increased to 2.5% in the short-term and up to 4.7% by 2030, with a required investment of 150 €/m2 (with a price decrease of 2% p.a.) for an average reduction of energy use by 70kWh/m2a (Meißner/Krause/Jaeger 2013). This would result in a reduction of energy use by approximately 66 Mtoe in 2030. The required investment needs are approximately €70-94 bn per year, hence €1372 bn accumulated from 2012 until 2030.

The net employment effect is often argued to be highest for more ambitious energy efficiency measures. Meijer et al. (2012) has presented a literature review with an employment effect of 12-17 new jobs per €1 million investment. With an employment effect of 14 person years per €1 million investment (and an annual reduction of 4%) there could be approximately 800.000 new jobs.

Energy efficiency measures are characterized by high upfront costs and a long payback time, posing challenges for new buildings as well as retrofitting. The challenge concerning improving building codes for new buildings is that incentives of builders and owners are not well aligned and upfront costs of a higher building standard are usually higher and the payoff rate is often intransparent for the builder/owner. The awareness and information level, as well as the assessment quality is rather low, increasing transaction costs for the owner. Concerning retrofitting, split incentives pose a particular challenge to increasing retrofit rates due to the high rate of rented buildings in Germany. Additionally, there is a difference between commercial and residential buildings. USers of the former will be less aware of operation cost management and therefore less likely to engage into retrofitting. These decision making processes are important for the model, as they determine the decision functions of the agents and need to be taken into account in policy decisions.

13.4 Transportation

The transport sector caused almost 25% of emissions in 2011 in the EU (1215 $MtCO_2e$), of which 70% are due to road transportation (of which again 70% are due to passenger cars), 14% due to water transportation, 12% due to air traffic, 1% due to railway transportation. The amount of transported goods increases and decreases with economic activity, as we could find a sharp decline in 2008 and 2009. Transport emissions increased by almost 40% from 1990 to 2007 and decreased by more than 10% from 2007 to 2009/2010 (highest impact on civil aviation and water transport).

For the transportation of goods, the lowest emissions per ton and kilometre (tkm) can be reached via water (13 g/tkm) and rail (20 g/tkm), compared to 75 g/tkm for road transportation. For passenger transport, the lowest emissions per passenger kilometre (Pkm) can be reached via water and rail (40 g/Pkm), which is much lower than 115 g/Pkm for air and road transport. However, the decrease in emissions by air transportation were highest, with 33% (EEA,2013).

The largest share of transport emissions is attributable to road transportation, amounting to almost 20% of all emissions. Additionally, road transportation is the most inefficient mode of transportation. This makes clear that changing transportation patterns away from road transportation as well as making road transportation more efficient, will be key in reducing transport emissions.

It was estimated by Meißner/Krause/Jaeger (2013) that emissions from conventional combustion engine cars can be reduced by 50% in 2030 compared to 1990. Emissions allowed for new cars in the EU were reduced from 172 gCO_2/km in 2000 to 132 gCO_2/km in 2012. A reduction to 90 gCO_2/km is scheduled to be implemented before 2030.

Necessary investments are due to higher sales prices for electric vehicles as well as infrastructure enhancement. The additional price for an electric vehicle was estimated to be €8,700. Applying a progress ratio of 0.75 will reduce the additional price for electric vehicles to €1,300 in 2030 (Meißner/Krause/Jaeger 2013). An increase in the fleet of electric vehicles to 1 million by 2015 and 40 million by 2030 (out of approximately 260 million vehicles in total), would result in accumulated additional investment needs of €92 bn. These can be amortized to a large extent by reduced fuel costs.

Investment required for new infrastructure was estimated to be around €1000-2000 per vehicle for hydrogen infrastructure and another €1500-2500 per vehicle for electric infrastructure. A rough estimate for investments in additional new infrastructure is €20-30 bn accumulated until 2030 (Meißner/Krause/Jaeger 2013).

13.5 Industry

GHG emissions from industry were reduced from 1321 MtCO_2e to 902 MtCO_2e (approximately 32%) between 1990 and 2011 (direct emissions from industry plus industrial processes). OECD/IEA 2007 estimated an additional potential reduction of carbon emissions by 19-32%, using existing technologies. With technological progress the potential savings can be even higher. Meißner/Krause/Jaeger 2013 estimate that for a 50% GHG emission reduction scenario, industry needs to reduce its emissions by 51% from 1990 until 2030.

Energy use in industry can mainly be attributed to chemical industry with 19%, steel production with 17%, non-metallic minerals with 14%, paper with 13% and the food industry with 11%. Except for the textile industry, all industries showed energy reduction improvements, the steel industry by 40% between 1990-2011, the chemical and non-metallic minerals industry by 20% over the same period (EEA 2013).

Generally, Eastern European countries have shown higher energy efficiency improvements, Bulgaria and Lithuania with 8% between 2000 and 2009, Poland with 5%. Germany has increased its energy efficiency by less than 0.25% over the same period (EEA 2013).

In general, investment needs in the industry are more cumbersome to estimate. It was found by OECD/IEA (2007) that most energy efficiency investments can be realized with short payback periods (as regular replacement investments), hence no additional investments are necessary.

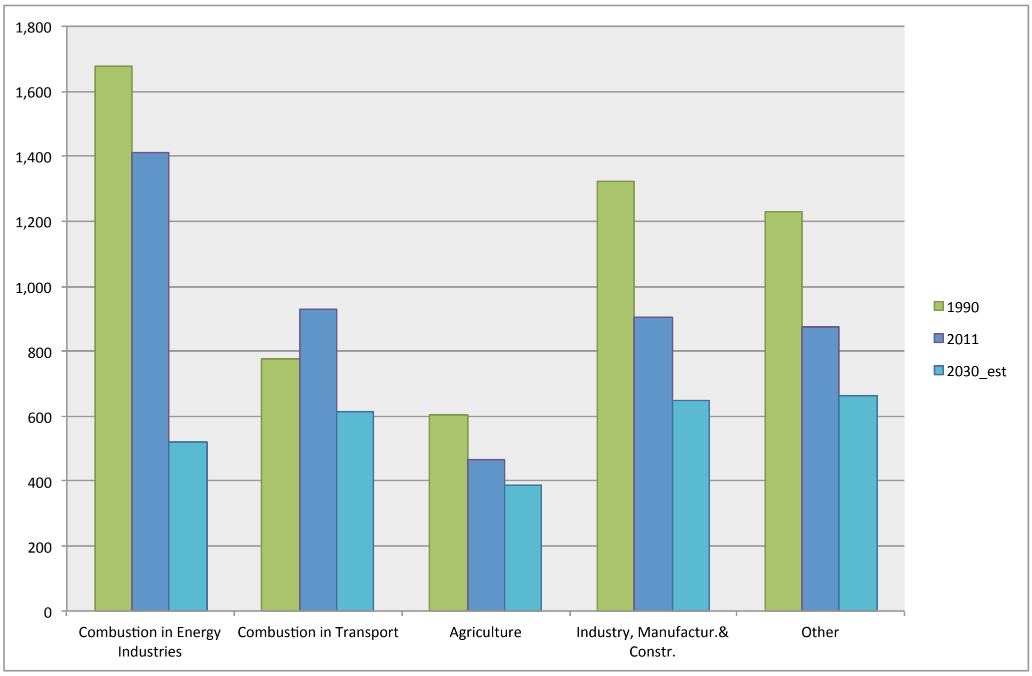
Investments in a reduction in electricity demand seem to be less attractive, as indicated by the fact that electricity demand has increased in the industry sector – in contrast to other energy sources. It is estimated that a reduction of 28 Mtoe would require additional investments of at least €1 bn and respective incentives.

13.6 Summary

For the purpose of enriching the modules under development we investigated emission, energy use, investment and technological learning curve data. Capital formation and investment are one of the main drivers behind a transformation to a more sustainable economy and hence an important model input. Investment is furthermore necessary for learning-by-doing, hence the learning curve effect is another important aspect. Last but not least, past and potential future emission reductions as well as energy intensity per sector are also important inputs.

The development of emissions by sector between 1990 and 2011, as well as the required reductions until 2030 to reach a 50% emission reduction target, can be seen in Figure 35. The contributions of each sector can differ depending on the dynamics in the economy as well as the institutional framework.

Figure 35: GHG Emissions by sector for 1990, 2011 and estimated for 2030



Source: eurostat(2014).

This section summarized the main findings regarding important sector information. A strong knowledge base on sectoral data and inter-sector relations is key for improving the integration of bottom-up information into macroeconomic models, one of the main goals of this project.

14 Documentation of sectoral models

14.1 Introduction

The modular architecture of STOEMSys models, and the open source nature, allow for the integration of information from existing sectoral models for assessing climate and energy policies. There is a wide spectrum of detailed bottom-up models focused on specific sectors – energy, transport, buildings, industry, etc. – that assess climate policy measures in terms of emission reductions, synthesized in policy scenario studies. To inform model development, an early milestone in the project was to document relevant models for analysing these sectors, most of which have been used in recent policy scenario studies for Germany. A very brief overview over a list of models, what kind of questions can be analysed with them, some main statements that have been derived from them, as well as the structure of inputs used and outputs provided by the models were presented in an earlier project report (Jaeger et al. 2012b). These brief insights into the models, and in particular into their input- and output-data structures, showed a great variety of modelling approaches (multi-agent, bottom-up, systems dynamics, optimization, linear programming etc.) for a great variety of objects under study (energy, industry, residential heat, transport, land use, economic and environmental questions, etc.). A commonality that observed was that most models represent the sector of interest in combination with a more generic representation of macroeconomic phenomena. This points to a possibility for integrating sector model information with a macromodule from STOEMSys: the macromodule could provide a framework of macroeconomic inputs as a common baseline to sectoral models. As background information for users of STOEMSys who might want to integrate information from existing sectoral models in open source mode, the documentation is again provided in this final report. For detailed model descriptions, the reader is referred to the respective model documentations.

14.2 Energy models

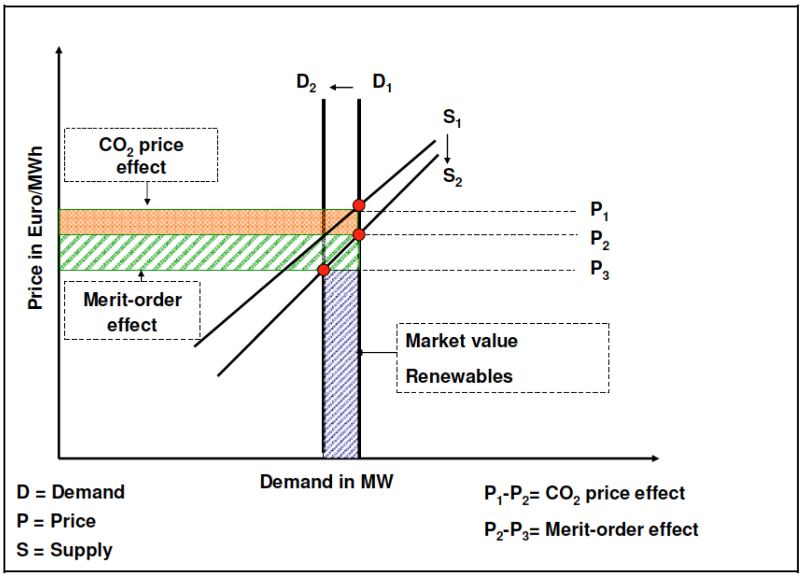
14.2.1 POWER ACE model

Power ACE is a simulation platform which has been developed by Fraunhofer Institute for system technology and innovation research (ISI). The model is especially used in the context of quantifying the merit-order-effect, as well as the price effect of renewable electricity generation on the CO_2 market (Sensfuß/Ragwitz 2008). The general conclusion is that both effects reduce the market price for electricity at the spot market.

The justification for the merit-order-effect is as follows: The guaranteed feed-in of renewable electricity, usually bought by supply companies, reduces the remaining demand for energy on the spot market. Reduced demand leads to lower prices on the market, since the market price is determined by the marginal cost of the most expensive plant running at each moment in time.

The justification for the CO_2 effect is as follows: The CO_2 savings effect of renewable energies reduces the demand for European Emission Allowances (EUA) and therefore the price for EUAs and in turn the price for electricity. The two effects are illustrated in Figure 36.

Figure 36: CO_2 effect



Source: Matthes et al. 2009.

The model design is depicted in Figure 37. The markets included in this model are the CO_2 market, the energy spot market as well as reserve markets.

The power generators can act as different agents, as supply trader on the spot market, as balancing trader or pump storage trader on the reserve market or as CO_2 trader on the CO_2 market. There are two kinds of investment planers, one for renewable power plants and one for conventional power plants. The investment decisions influence the capacity of the respective energy source. Grid operators place bids on the reserve market and sell renewable energy, bought from the renewable agent, on the spot market.

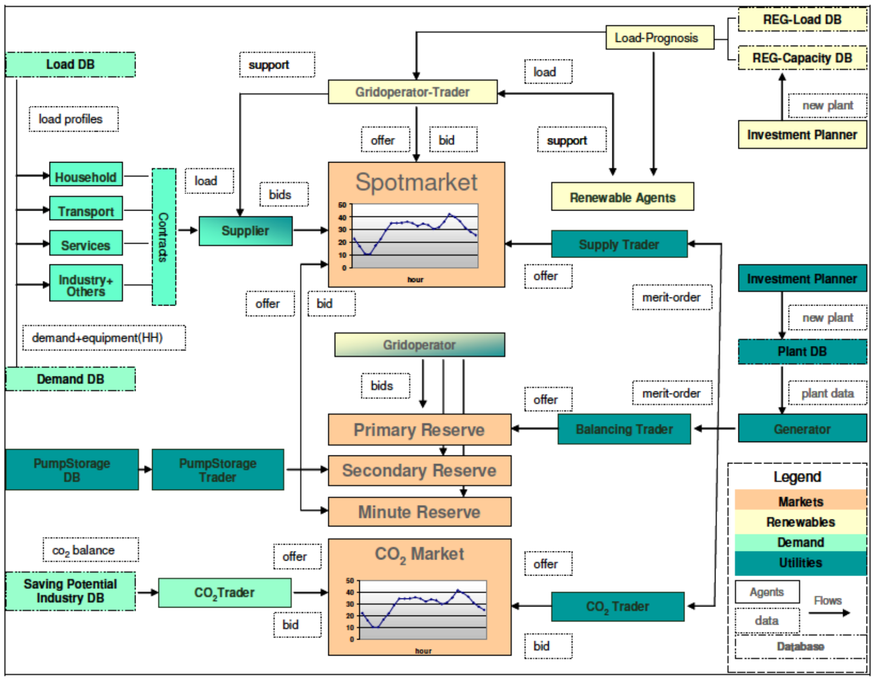
The energy suppliers place bids on the spot market and have contracts with different consumers (households, industry, transport and services).

Several databases serve as input for the agents in the model: CO_2 savings potential of industry database, conventional plant database, pump storage database, renewables capacity database, renewables load database, and a load and demand database.

14.2.2 POWER ACE ResInvest model

The model Power ACE ResInvest, also developed by Fraunhofer ISI, is used for policy scenarios (Matthes et al. 2009), determining the expansion of renewable energy production (in TWh/year) as a reaction to different market circumstances, policies, and subsidies. The model is an agent-based energy market simulation model.

Figure 37: PowerACE model



Source: Matthes et al. 2009.

The agents are 1) investors/project developers 2) technological learning 3) producer 4) permission. Investors take an investment decision based on investment costs and cost potential (endogenous), energy prices (exogenous) and subsidies (exogenous). Investment costs are adjusted depending on the degree of technological learning. However, the final building decision depends on the permission, which in turn depends on the demand for energy (exogenous), a diffusion parameter (exogenous) and the potential (exogenous).

The producers of power plants adjust their production capacity, respectively. An increase in production capacity depends on the utilization and the maximum possible capacity expansion. The output variable is the (change in) renewable energy capacity.

14.2.3 ELIAS (electricity investment analysis) model

ELIAS is a capital cost and investment model for the overall energy sector developed by the Öko-Institut Berlin and used for policy scenarios (Matthes et al. 2009). It serves as a tool to calculate investment activity in the energy sector, depending on different policies and certain costs structures.

Examples of policies assessed are the abolition of the natural gas tax, the introduction of the EU emission trading system, co-generation subsidies and avoided grid charges.

A power plant database, containing the age structure of all power plants, serves as input for the model. If cost differences between two kinds of power plants are very small, some suboptimal power plants will be built, which is specified by a fuzzy function. Minimum targets for a certain technology (e.g. renewable energies) can be added, as well as maximum targets, representing resource constraints (e.g. hydropower stations). To balance fluctuating solar and wind electricity, additional flexible power plants are built (e.g. gas power).

Two main outputs can be generated when using the model: 1) the investment needs resulting from old power plants going out of operation, and 2) the kind and size of new power plants to be constructed, based on a return on investment calculation.

14.2.4 PowerFlex model

The Power Flex model is an electricity market model, developed by the Öko-Institut Berlin. Using this model, the operating time of power plants and the resulting returns are calculated. With this data, the effect on the electricity price can be estimated.

The operating time of power plants and storage as well as adjustments in flexible demand are determined according to detailed demand and supply data. The goal is to optimize costs and CO_2 emissions depending on demand and supply properties.

The model can be interlinked with the ELIAS model.

14.3 ISI Industry model

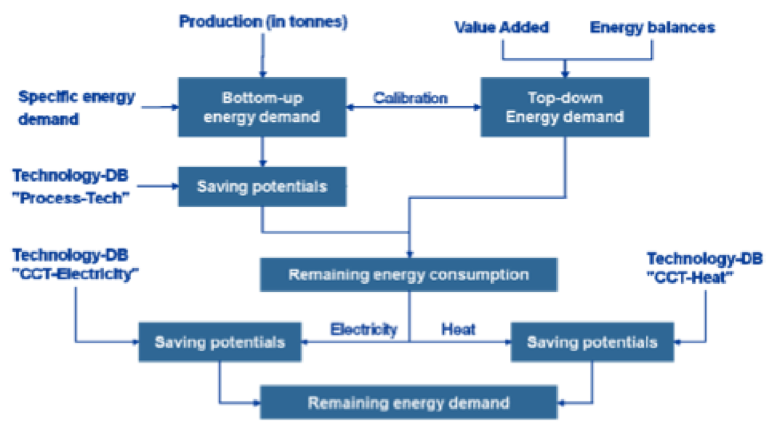
ISIndustry is a bottom-up model, used primarily for the simulation of the final energy demand of different industries, based on technological information about industrial processes and the type of energy used. The model therefore distinguishes between process-specific technologies and cross-cutting technologies, where the latter are technologies used in different industrial sectors, for example lighting equipment. The model includes 50 types of process-specific technologies that together account for more than 50 percent of industrial fuel consumption and 30 percent of energy consumption. The remaining energy demand is aggregated via cross-cutting technologies in less energy intensive industries. The simulation model is based on empirical findings of different engineering studies. Together with data on value added and energy efficiency, which may also change over time, ISIndustry calculates the investment in energy efficiency measures and the final energy demand.

ISIndustry is able to simulate potential changes in energy efficiency and their effects on the long-term energy demand and CO_2 emissions. Because it contains the cost and efficiency structure of different options in the industrial sectors, the model can give information about the effects of different economic policies such as taxes on energy prices or emission trading.

14.4 IKARUS model

The IKARUS residential heat model (Raumwärmemodell) was developed by a group of research institutions: Research Center Jülich (STE), German Institute for economic research (DIW), Fraunhofer ISI, and five further partners (Markewitz/Stein 2003). IKARUS consists of an extensive database and several computer-based models, briefly described below. The aim of the model is to calculate the demand for heating, fossil fuels and CO_2-emissions, based on a comprehensive building and heating typology. Using the database of the existing building

Figure 38: ISIndustry model



Source: ADAM M1 ISI Fraunhofer.

stock and different forecasts on changes to it, the potential for emission savings can be determined. IKARUS is dynamic and takes into account time dependent developments in form of exogenous scenarios.

IKARUS has been used to calculate and evaluate the incentive programs by KfW banking group (government-owned development bank). The purpose was to estimate the financial savings for households refurbishing their residential buildings, as well as the change in CO_2 emissions for the production sector. For the residential buildings, realistic energy saving scenarios were calculated. The CO_2 savings were calculated using information on the recent heating structure and respective CO_2 coefficients.

470,000 apartments were refurbished until the end of 2001 within the framework of the KfW loan program. This can serve as a representative sample for the entire building stock, consisting of 10 million individual buildings. To reduce the large variety of building types for the model calculations, all buildings were systematically reduced to around 60 representative building types, with a building typology developed for this purpose. Using the model, different refurbishment measures can be applied to different building types and their effects on consumers can be calculated. The impact of a measure can then be extrapolated over the entire stock of refurbished houses.

14.4.1 Optimization Models and Partial Models

The optimization model delivers results about overall economic questions, including interdependencies within the energy system. This model serves to analyse national greenhouse gas strategies. The energy system of Germany is represented in the form of interconnected processes. The model uses linear programming to fulfil the energy demand while producing minimal costs, given certain constraints, including energy policy goals.

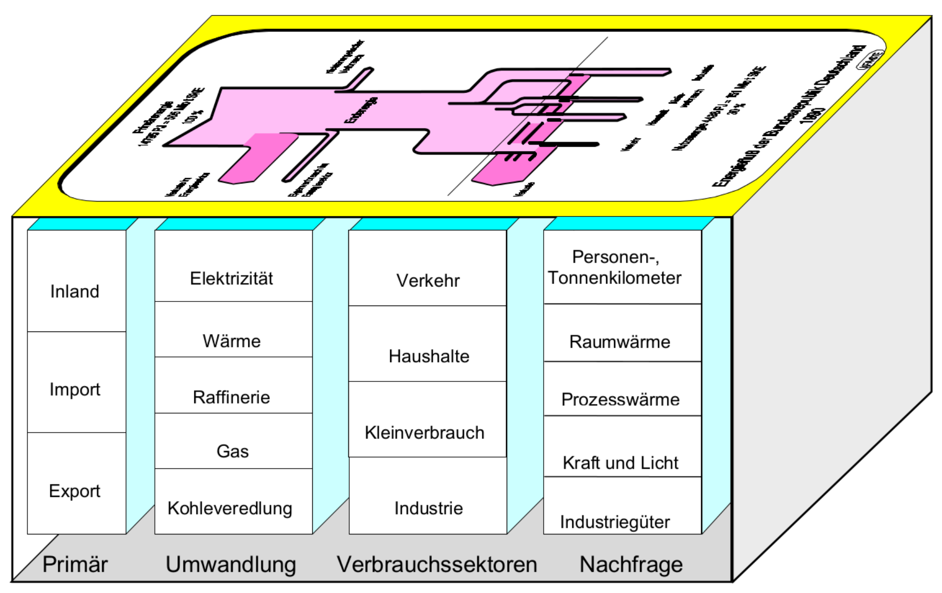
There are partial models for the industry sector, the building sector and the transport sector. They enable sector specific considerations which can deliver parameters for the overall energetic considerations in the optimization model. The instrument consists primarily of technical descriptions on the level of the energy demand and energy supply and therefore can reproduce the energy flows and energy conversion.

The partial models are directly linked to the database. The energy demand in each specific sector is derived from the demand for its products. The calculations include emissions and costs for energy efficiency measures. Possibilities for emission reduction through individual measures or packages of measures can be determined. Transport services are recognized depending on transport mode, purpose of journey, as well as energy efficiency and emissions.

14.4.2 Macro-economic Information Model (MIS model)

MIS is a dynamic, demand driven input-output-model with a detailed description of the energy producing and energy consuming sectors in Germany. This is illustrated in Figure 39.

Figure 39: Structure of the MIS model



Source: Markewitz/Stein 2003.

The calculations are based on sector specific data for energy-, transport-, and industry- and other sectors and aggregate data from input-output tables from the Federal bureau of statistics. The model uses a production function with constant elasticity of substitution (CES) where factor inputs can be substituted, e.g. different kinds of energy can be used, depending on the price development. The results can be used to check for consistency within the optimization model, and they deliver macro economic input for the optimization model.

14.4.3 Data

The input database contains inventory of buildings (classified into about 60 different building types), as well as technical, economic and environmentally related data on specific technologies (e.g. gas turbines, thermal heat pump).

Macroeconomic data contain the status-quo as well as different scenarios for macroeconomic development, demographic development and prices for different energy sources.

For each partial model the output contains emissions and costs for energy efficiency measures.

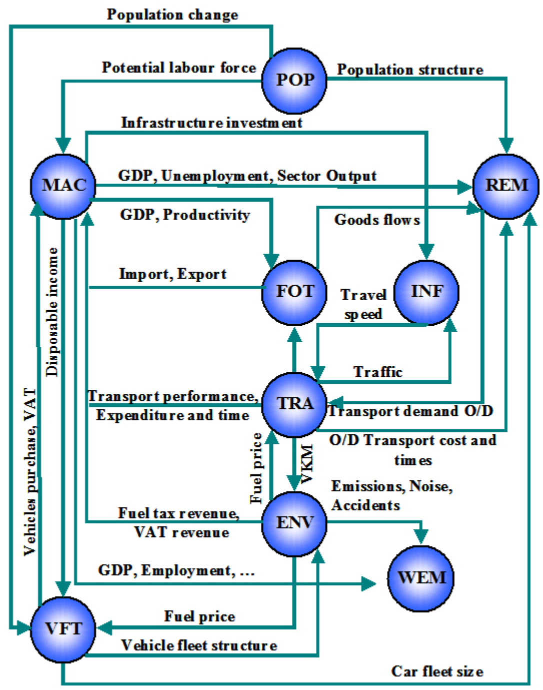
14.5 ASTRA model

ASTRA, developed and maintained by Fraunhofer ISI and TRT, abbreviates “Assessment of Transport Strategies”. The model was developed as a tool to strategically assess European transport sector policy, with a longer term time horizon. It analyses impacts of various policies related to transport but also technology, employment, renewable energy, or climate and scenarios on the transport system, the economy and the environment. Among these are emissions and efficiency standard setting, infrastructure pricing, fuel taxation, speed limits, carbon taxes, trade policies, subsidies, feed-in tariffs, the EU-ETS, investment strategies, and energy scenarios. Timing and levels of policy implementation are flexible and integrated policy packages can be analysed.

ASTRA has been used in various projects, also in combination with other models, for example to assess German climate and energy policy measures (Politikszenarien); to link R&D, transport policies and reduction targets (GHG-TransPoRD project); to assess the effects of high oil prices (HOP! project); to extend the European policy assessment toolbox so that it can capture the implications of alternative technologies and new energy carriers entering the transport markets (iTREN-2030 project); and to assess social and economic impacts of past and future sustainable transport (ASSIST project). Results of such applications of ASTRA (and other models), especially for Germany (see Matthes et al. 2009), include that introducing VAT for international air traffic as well as abolishing electricity taxes for railway traffic show relatively little effects, whereas an extension of road charges for freight traffic, a stricter CO_2 strategy for cars, a general speed limit of 130km/h on highways, a comprehensive taxation of kerosine, and a CO_2-dependent taxation of staff cars can yield significant reductions in energy demand for transport and in CO_2 emissions. The most effective measure is the kerosine taxation, that can break the increasing trend in emissions from air traffic. In order to reap the benefits from these measures, they have to be accompanied by measures such as support for technology development.

An official documentation of ASTRA can be found under http://www.astra-model.eu/index.htm. The model covers EU27+2 countries and integrates a population module, a macroeconomic, a regional economic, and a foreign trade module, an infrastructure module, a transport module, an environment module, a vehicle fleet module, and a welfare measurement module. The various links between the modules are displayed in Figure 40. Emissions and accidents, the government, employment and investment are represented within the modules. The economic parts of ASTRA use input-output tables that, in some versions, contain 25 sectors. The model builds on recursive simulations following the system dynamics concept and allows to run scenarios until 2050. The applied Vensim system dynamics software provides sophisticated tools for sensitivity analyses.

Figure 40: Module structure of the ASTRA model



Source: http://www.astra-model.eu/structure-overview.htm, visited Oct 8, 2012.

The detailed representation of the transport system uses two classical 4-stage (trip generation and distribution, choice of mode and routes) transport models for passenger and freight transport, which consider endogenous reactions on all stages, that is, the effects of policies can be reflected at all stages. These models are embedded into several of the above mentioned modules. Inputs include GDP, wages, fuel prices, population, and employment for the passenger, and GDP, monetary trade flows, sectoral production, and value-to-volume ratios for the freight transport module. The regional economic module generates transport demand (i.e. trips). Based on transport cost and transport time matrices, the transport module performs the modal split for five passenger modes and three freight modes, computing also transport expenditures and vehicle-km. Using information on national compositions of vehicle fleets, the environmental module translates vehicle-kilometres travelled per mode, distance band, and traffic situation into fuel consumption, emissions, and fuel tax revenues from transport. A variety of further indicators is estimated with the ASTRA model, and these indicators are provided as time series.

14.6 TREMOD model

The TREMOD model, developed by ifeu – Institut für Energie- und Umweltforschung Heidelberg GmbH on behalf of the Umweltbundesamt, uses a bottom-up approach to calculate the emissions of overall traffic in Germany [see the webpage of the Umweltbundesamt: http://iirde.wikidot.com/road-transport]. It considers passenger and freith traffic and differentiates the possible kinds of transportation. Basis data is used from 1960-2010 containing performance, transport capacity, capacity utilization rate, technical properties of inventory, as well as energy and emission factors. The model enables to calculate traffic, energy consumption and emissions according to transport type. It has been used to create different scenarios for the energy consumption, the development of different fuel use, the emissions of air pollutants and greenhouse gas up to 2030 (Knörr et al. 2011).

TREMOD serves to prepare decisions concerning traffic policy by using different scenarios. Different organisations as the Deutsche Bahn AG and Lufthansa use the TREMOD model [see http://www.ifeu.de/index.php?bereich=ver&seite=schwerpunkt_bilanzen_szenarien].

14.7 CAPRI model

The CAPRI model (Common Agricultural Policy Regionalised Impact analysis model) is a quantitative agricultural sector modelling system of the EU27, Norway, Turkey and the Western Balkans. It consists of a supply and a market module which are linked via an iterative procedure. The documentation and additional information concerning general information, the data base and the two modules can be found on the homepage of the model http://www.capri-model.org/dokuwiki/doku.php?. The first "consists of independent aggregate non-linear programming models representing activities of all farmers at regional or farm type level", the second is a comparative-static, deterministic, partial, spatial, global equilibrium model (Britz/Witzke 2011).

The modelling system serves to evaluate effect of policy instruments of the agricultural sector on production, income, markets, trade, and the environment both at national and subnational level. CAPRI has been applied to investigate farming sustainability and reform options for the sugar market and to analyse tradable permits for greenhouse gas emissions, the effects of bi-lateral trade liberalisation with Mediterranean countries and options to abate ammonia and nitrates emissions.

The database contains data at global, national and regional level. These are market data, data concerning the agricultural sector, trade flows and trade policies as well as domestic market support and common agricultural policy instruments. Economic indicators such as revenues, costs, etc. are calculated in an input allocation step.

Output of the following classes is given: Cereals, Oilseeds, Other Annual Crops, Vegetables, Fruits, Other perennials, Fodder, Marketable products from animal production, Intermediate products from animal production, Other Output from EAA.

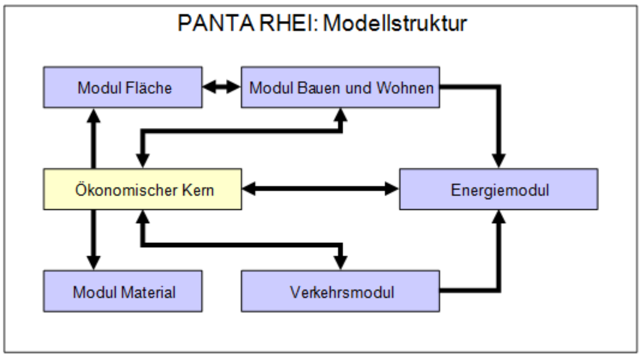
The following inputs are given (also given by classes, all in all about 35): Mineral and organic fertiliser, and Seed and plant protection, Feeding stuff, Young animal and Other animal specific inputs, General Inputs.

14.8 PANTA RHEI

PANTA RHEI is a highly endogenous macroeconomic model of Germany, developed by GWS (Gesellschaft für Wirtschaftliche Strukturforschung mbH) to analyse economic and environmental questions (Lehr et al. 2011). Modelled agents are rational only to some degree. The model has been used, for example, to investigate renewable energies and their development in the context of employment, respectively the labour market, to evaluate energy scenarios of an energy concept and to analyse material usage as well as to project future land use.

PANTA RHEI is a sectoral model with input-output structures and uses an iterative solution procedure. It contains an economic kernel as well as 5 modules (energy, traffic, material input, land-use, dwellings). Figure 41 shows the structure of the model.

Figure 41: Model Structure of PANTA RHEI



Source: http://www.gws-os.com/de/content/view/52/40/.

The economic kernel is formed by the econometric evolutionary model INFORGE, developed by GWS as well. It uses input-output tables and national accounts as supplied by the Federal Bureau of Statistics. Exogenous variables are mainly taxes, labour supply and world market data. INFORGE calculates macroeconomic variables (e.g. gross income) which influence variables of all other modules. The data for the energy and environment sectors include energy balances, energy data of BMWi, e.g. prices of CO_2 certificates, traffic, and housing and buildings statistics. The energy module contains 20 different types of consumers of end-use energy and 30 different energy sources. It is possible to include exogenous information in the model, to represent political measures or to adapt any behavioural equation. Different scenarios of demographic development can be used in PANTA RHEI, important variables (e.g. building investment) change accordingly.

PANTA RHEI can be used to explore the impact of important influencing factors for example on variables such as energy prices, BIP, employment. It enables to explain and project the input-output variables endogenously. The relations between economic development, use of energy and CO_2 emission is included in the energy model. It also provides the modelling of primary energy consumption, consumption of end-use energy and transformation. The traffic module adjusts the vehicle pool and fuel consumption, the land-use module the energy demand due to heating. The traffic module distinguishes passenger and freight transport and provides prices, performance and energy use for any mode of transport.

Based on PANTA RHEI, the model PANTA RHEI REGIO, also developed by GWS, turns attention to land-use on a regional level (see Ahlert et al. 2007; Distelkamp et al. 2009).

PANTA RHEI REGIO is used to create scenarios describing land use in Germany and investigating economic and ecological effects of fiscal policy and public measures. Three types of land use are distinguished: housing, industry/business and traffic (Ahlert et al. 2007). The model serves to analyse sustainable spatial and settlement development on a regional and supra-regional level. It has been used to estimate consequences of a limitation in settlement and fiscal steering.

The necessary data on a regional level for the model covers land use, buildings, labour market, economy, income, building ground and population with sub-categories like number of households, commuters, housing stock, building activity, etc. (Distelkamp et al. 2008). Output data is the amount of land use up to 2020.

15

Conclusion

In a situation where mostly single-equilibrium models were used to assess costs and benefits of climate policy, and these assessments mostly came to the conclusion that climate change mitigation involved sacrificing welfare in the short-term, the project “Bewertungsmodul Klimapolitik (BMK)" set out to build a macro-economic module that could represent multiple equilibria, and that could be combined with models providing detail on emission relevant sectors, so as to identify win-win strategies for climate policy. This goal was rather far from mainstream climate policy modelling, and the approach chosen to tackle the challenge, agent-based modelling, is relatively recent in economics, and, compared to mainstream approaches, has produced few policy relevant outputs. It was however necessary to choose an approach that represents the economy as a complex system of heterogeneous agents in interaction to capture important mechanisms such as expectations, coordination, and learning-by-doing.

After almost three years of project work, this final report presents STOEMSys, the Sustainability Transition Open Economic Modelling System created by this effort. It provides macroeconomic modules that can be combined with sectoral modules and represent multiple equilibria, and preliminary simulations indicate a win-win strategy in form of a green investment impulse. However, modules are not yet in a state where they can be readily applied to their ultimate purpose of assessing costs and benefits of climate policy. At the same time the system supplies much more than these modules. It consists of economic, computational and implementation components that provide a framework necessary for producing, coupling and using modules that can identify win-win strategies for climate policy.

Using a non-standard approach meant that complementary work was needed, from assembling the necessary economic concepts (resulting in the economic components of STOEMSys) via providing a computational toolbox and infrastructure (resulting in the computational components of STOEMSys) to implementing some of the economic concepts as building blocks for several modules that could be used for the different purposes of understanding principles of economic mechanisms and simulating real-world economic systems. While some of the challenges were known from the beginning, others turned up in the meantime. STOEMSys is a way of sharing this experience, in addition to the work done, with other researchers working towards models that can analyse policies for a sustainability transition.

While the project BMK ends, STOEMSys is research in progress. Further work, particularly on STOEMSys models for policy simulation is certainly needed, is interesting, and will be done. Having entered pretty much untrodden terrain, nevertheless, the way forward is promising:

- Preliminary simulations indicate that investment-oriented climate policies can shift the economy to a new growth path with lower emissions but higher growth. This finding is complemented by work from related research activities at GCF: enhancing single-equilibrium models one arrives at these findings as well.

- The out-of-equilibrium dynamics implemented in STOEMSys models introduces money, that is usually not present in standard single-equilibrium models of the economy (these then use relative prices). This opens up the possibility of representing the financial system more explicitly, and hence to analyse questions regarding the interactions between financial and real economy. Climate finance, and questions like which instruments can facilitate a sustainability transition provide scope for further research.

A Center of Excellence for Global Systems Science is in preparation. The scientific domain of Global Systems Science tackles the problem of developing evidence and understanding concerning global systems and related policies. The center will employ high performance computing (HPC) to address several topics, among which green growth, in particular the global diffusion of green growth initiatives. GCF work for this research activity will benefit from the foundations laid with STOEMSys.

Schlussbemerkung

Hauptergebnis des Projekts Bewertungsmodul Klimapolitik (Förderkennzeichen 03KSE041, Mai 2012 - Dezember 2014) ist STOEMSys (Sustainability Transition Open Economic Modelling System), ein offenes ökonomisches Modelliersystem für eine Nachhaltigkeitswende.

Weil sich im Projektverlauf ergab, dass die ursprüngliche Anforderung, ein Modul zur Kosten-Nutzen-Analyse klimapolitischer Maßnahmen im ökonomischen Gesamtzusammenhang zu entwickeln, zu kurz greift, ist das Ergebnis ein Modelliersystem. Das ursprünglich geplante makroökonomische Modul sollte durch die Darstellung mehrerer ökonomischer Gleichgewichte die Analyse von Win-Win-Strategien im Klimaschutz ermöglichen. Es wurde ein agentenbasierter Ansatz gewählt, um relevante Mechanismen, wie z.B. Erwartungen von Akteuren und eine Dynamik, die sich aus diesen Mechanismen ergibt, darstellen zu können. Agentenbasierte Modelle werden auf dem Computer implementiert, indem man die Agenten mit Regeln für Entscheidungen und Interaktionen ausstattet. Das Systemverhalten wird dann durch Simulationen, die sich aus wiederholten Interaktionen der Agenten ergeben, beobachtet und kann schnell sehr komplex werden. Agentenbasierte Modelle für die Simulation politikrelevanter Fragestellungen einzusetzen, stellt daher eine große Herausforderung dar.

Um diese anzugehen, waren viele auf einander aufbauende Arbeitsschritte notwendig, und so wurden einige der größten Herausforderungen erst im Lauf des Projekts deutlich. So ist z.B. die Darstellung einer Preisdynamik außerhalb von Gleichgewichten in der ökonomischen Modellierung relativ neues Terrain. Deswegen wurden, um neben Simulationen auch grundlegendes Systemverhalten studieren zu können, statt nur einem makroökonomischen Modul verschiedene Module von unterschiedlichem Grad an Vereinfachung entwickelt. Das Modelliersystem stellt damit nun eine breite Basis dafür dar, neue Modelle zur Simulation von Kosten und Nutzen der Klimapolitik zu entwickeln.

STOEMSys besitzt eine modulare Architektur, auch um bestehende Modelle, die einzelne Sektoren detailliert darstellen, nutztbar zu machen. Schließlich ist es für die Bewertung von Klimapolitik erforderlich, dass die Sektoren, die für die meisten Treibhausgasemissionen verantwortlichen sind, detailliert dargestellt werden können, gleichzeitig aber die Makroökonomie nicht aus den Augen verloren wird. Somit kann das System in Verbindung mit externen Modellen verwendet werden, ist also in dieser Hinsicht offen. Aber auch in einem weiteren Sinn handelt es sich bei STOEMSys um ein offenes System: alle Implementierungen stehen als Open-Source-Software zur Verfügung. Einsehbarer Quelltext und die umfassende und verständlliche Dokumentationen von Modellen zur Bewertung klimapolitischer Maßnahmen sind notwendige Schritte auf dem Weg zu mehr Transparenz von Simulationsergebnissen und somit einer neuen Qualität in der Fachdiskussion.

Das Projekt BMK ist beendet, STOEMSys als Forschungsprozess aber nicht abgeschlossen. Weitere Arbeit ist erforderlich und wird im Rahmen des Green Growth Forschungsprozesses am GCF durchgeführt werden, damit auf der Basis von STOEMSys ein einfach einzusetzendes Simulationsmodell für die Bewertung von Klimapolitik entsteht. Vorläufige Simulationen zeigen jetzt schon vielversprechende Ergebnisse: investitionsorientierte Klimapolitik kann nicht nur Emissionen senken, sondern gleichzeitig auch helfen, die Wachstumsschwäche der europäischen Wirtschaft zu überwinden. Dies erfordert die Lösung eines Koordinationsproblem auf Investitionsmärkten: Die Gewinne einzelner Investoren hängen davon ab, wie gut sie die Wachstumsperspektiven der Wirtschaft einschätzen. Umgekehrt hängt aber auch die gesamtwirtschaftliche Entwicklung von diesen individuellen Erwartungen ab. Die Erwartungen sind also selbstverstärkend. Eine investitionsorientierte Klimapolitik mit ambitionierten Zielen kann über eine glaubhafte Perspektive "grünen" Wachstums diese Erwartungen neu koordinieren. Ein "grüner" Investitionsschub umfasst dabei unter anderem den Umbau des Energiesystems sowie die energetische Sanierung der Gebäudesubstanz.

Traditionell wird Klimapolitik oft als eine Verschiebung von Investitionen hin zu "grünen" Technologien und Produkten analysiert. Dies reicht nicht aus um eine europäische Energiewende unter den gegebenen Bedingungen der nur langsam abklingenden Eurokrise zu untersuchen, weil in beiden Fällen zusätzliche Investitionen notwendig sind. STOEMSys bildet eine Grundlage für die Analyse von Politikmaßnahmen, die dies berücksichtigen.

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Annex

A

Stakeholder Dialogues: Workshop- and Conference-Programmes, Presentations by GCF Staff

B

GHG Emission Reduction Scenarios