1. INTRODUCTION

In Europe, the share of renewable energy on the net electricity production is growing steadily over the last decades. This is mainly due to a strong promotion of wind and solar power by the European Union and its member states. Since the promotion of renewable energies first started in the year 2001 with the Directive on the promotion of the use of energy from renewable sources [2001/77/EC] (actual version [2009/28/EC]) all member states adapted an adequate regulatory and market framework for renewable energies to support the fast growth towards a sustainable energy supply system, see [NREAP]. In the European Union, the installed power of just wind power and photovoltaics increased in absolute numbers from around 14 GW in 2000 to more than 180 GW in 2012 [IEA 15], [OBS 15], [EWEA 10], [EWEA 13]. This is a total rise of 1290 percent in just 12 years and development is still highly dynamic. Especially wind and solar power have witnessed a very fast growth in the last decade. However, wind and solar power are dependent on natural conditions like wind speed, global radiation, temperature etc. These natural resources are free of charge but not controllable in their intensity and consistency.

This poses some major problems to future energy and especially electricity supply systems, because the supply system will depend mainly on fluctuating energy carriers. Two main problems will have to be handled in an energy supply systems based on these types of renewable energies, the areal and temporal balancing. The areal balancing will be needed because energy will not be produced near the big load consuming areas but in regions with the best natural resources. To bring the energy to the consumer, transmission and distribution system extension and reinforcement will be needed [BECa13], [TYNDP 14], [FEI 12]. The temporal balancing is a more complex issue to address, because there are various technical options including demand side integration, import/export of energy, excess installation of renewable energy producing units, using excess energy for other sectors like the heating and transport sector and last but not least storing the energy during times of surpluses and providing it during times of shortages.

All these options will have a share in the final solution, but the particular share will still have to be defined. The question that has to be answered in the upcoming years is how much of each measure will be needed to fulfill the political goals of renewable energy integration and CO_2 emissions on the one side and to maintain the system stability and the security of supply on the other side. The achievement of these goals has to be investigated against the background of economic considerations like minimum electricity generation costs. This can only be done by modeling the supply system under certain scenario assumptions.

1.1 Motivation

Energy system modeling is a crucial part for the transformation of the energy supply towards a renewable based system [HER 12]. Energy models are increasingly used to provide insights into how energy systems may evolve in the years ahead [IEA 15]. These insights are needed to formulate political goals on the one side but also to develop strategies for companies, suppliers, producers etc. (see e.g. [BHA 10], [KEI 12]) on the other side. The models reach from top-down models with a macroeconomic approach and timely resolutions from weeks to years [HER 12], [HUB 04], [KUH 12], [LOU 04], [MES 95], [RIC 03] to system dynamics models with timely resolutions from milliseconds to seconds [DIG 15], [MAT 15]. Top down models focus on the integration of very comprehensive framework conditions of the energy supply systems like global economics, supply of primary energy, labor market, politics etc., whereas system dynamic models focus on a maximum detailed modeling of technical aspects of investigated technologies. For the modeling of forecast scenarios of the energy sector including network power flows, power plant dispatch planning, renewable energy integration, energy storage system operation and the impact of available flexibility options, top-down models do not provide a sufficient degree of technical detail, whereas system dynamic models are too detailed to allow the investigation of large systems. Against this background a lot of new energy system models have been developed in the last years [LUN14], [SCH 12], [EMD], [HEIa10], [HEI 11], [BECb13], [ROD 13], with a timely resolution of 15 minutes to days, aiming to include as much technical detail of the modeled technologies as possible to still allow the simulation of complete electricity and energy systems. These models will be called system dynamics superordinate (SDS) models within this work.

Within energy system models, especially the electricity supply system is very important to model adequately as it offers less degrees of freedom concerning the deviation between consumption and production. The electricity sector is also the one where strategies on how to overcome the challenges that are posed to systems with high shares of renewable energies are discussed to a very high extend. However, there is no agreement on how these challenges can be overcome. The solutions are wide spread, including grid extension, demand side management, energy storage systems, smart grids, flexible conventional power plants, cross-sectoral energy consumption and production etc.

Although there is a great variety of system dynamic superordinate models, the solutions provided by these models mainly focus on only one or few of the above mentioned topics and mutual interactions are often neglected. Additionally, most models just focus on forecast strategies or future technological deployments. Furthermore, programming algorithms or mathematical frameworks of most models are not available. The impact of scenario assumptions on modeling results is often neglected. To evaluate the impact of these singular factors or their interactions, a multi-parameter modeling is needed, where the area and complexity of the system under investigation can be freely defined, depending on the available data. This can only be achieved with a generic optimization tool with an open and comprehensive mathematical and programing framework.

1.2 Objective and structure of the thesis

The aim of this thesis is to develop a new tool for energy system modeling including technical as well as non-technical considerations and closing the gap between physics based system-dynamic models and projection models. Furthermore, economic considerations should be integrated to allow the evaluation of different future development scenarios of the energy sector against the background of overall system costs. The model will be developed for the electricity sector but possibilities to integrate the sectors heat and transport will be pointed out. The developed tool will be part of system dynamics superordinate models, but allowing a much more differentiated investigation of the system under investigation through the use of a generic optimization algorithm. The main target criteria for the new model can be summarized as follows:

- Deterministic model based on mathematical optimization. The same input produces always the same output
- Timely resolution from 15 minutes to hourly values
- Simulation time is not limited to a certain period. Different simulation options available for simulation times of few hours to multiple year
- Network model for the investigation of interconnected systems based on graph theory. Import/Export approximated as DC power flows with limitations and not only as additional flexibility option as in many other models
- Complexity of system can be modeled according to available data. Units can be modeled aggregated per technology or as standalone unit
- Free optimization target definition, which allows
    - the integration and combination of political or market regulatory targets with technical or economic ones by formulating adequate second order conditions
    - optimizing the complete system or just selected parts of it
- Free definition of optimization horizon, which allows a realistic model of day ahead and intraday dispatch planning
- Integration of a dynamic cost calculation approach for the calculation of dynamically changing electricity generation costs
- Generic modeling and programming framework allowing new technologies to be added easily without changing the programming code

At the end it should be possible to study the influence of different framework conditions (technical, economic and political) on the power plant dispatch, energy storage needs and operation strategies, load flows, CO_2 emission and costs. In general, a transparent and reproducible approach to model energy supply systems is carried out, which up to date is still missing in research and literature.

The basic structure of this thesis is displayed in Fig. 1-1. Following the introduction, chapter 2 focuses on the state of the art of energy supply systems in Europe and the development of fluctuating renewable energies as well as energy storage systems. Based on the presented development a need for energy system modeling is carved out. Existing approaches to energy system modeling as well as relevant models are highlighted and discussed and academic voids pointed out. Needs for a new model are concretized and target criteria for the implementation formulated. Furthermore, the benefits of the developed Energy System Optimization Studio (ESOS) are highlighted.

The third chapter describes the implementation of the developed ESOS modeling framework. ESOS and all its different parts are explained. As a first part the general structure of ESOS is discussed, followed by the description of the mathematical and programming framework. The next subchapters highlight the mathematical structure of the implemented technologies and actors in an electricity supply system. This includes general technical but also economic constraints. Furthermore, a newly developed, dynamically adapting, recursive calculation approach for the Levelized Costs Of Electricity (LCOE) is presented. An important topic in modeling high renewable electricity systems is the implementation of renewable energy production curves. There are different ways to obtain these curves, leading to different results. The last subchapter discusses different operation and optimization strategies of energy storage systems and other available flexibility options like Demand Side Management (DSM) and electric vehicles.

Chapter 4 focuses on the application of the model. First, the initialization process in ESOS is explained. This includes the general system design, global values, optimization framework settings as well as the definition of economic and technical values for the implemented technologies. After that, different application examples are carried out, divided into investigations of islanded and interconnected systems. Islanded system scenarios include small home scale systems as well as electricity systems of various countries. Interconnected system scenarios focus more on transmission needs and power flows of regional and international supply systems, against the background of various targets, e.g. regional autarky, grid extension vs. energy storage needs, synergies of timely correlation of renewable energy feed-in. As a last part of this chapter, general flexibility investigations are presented.

In chapter 5 sensitivity analyses are carried out focusing on the influence of the different assumptions regarding input parameters as well as framework conditions on the modeling outcome. This includes basic framework conditions like optimization settings and timely resolution on the one side, and more specific input data like technical and economic parameters of different technologies or different development paths of CO_2 certificate and fuel prices on the other side. Furthermore, the influence of variable framework conditions concerning the security of supply is highlighted. The different results are discussed critically.

The sixth and last chapter summarizes the presented results and the key features of the developed energy system modelling tool. Furthermore, it gives an outlook on possible improvements of the algorithm and points out concepts for the afteruse.

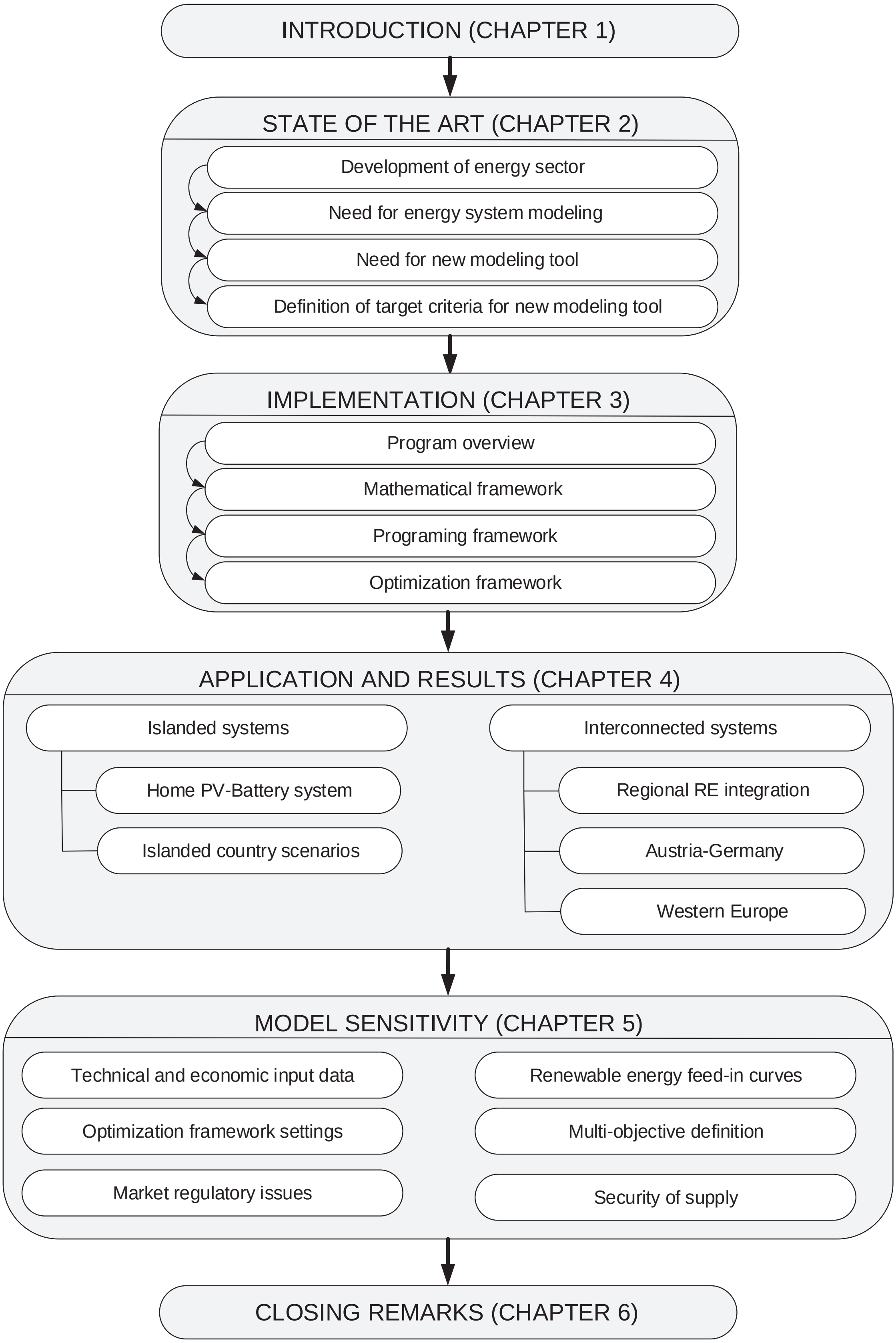

Fig. 1-1 Structure of the presented thesis