INTERDISCIPLINARY MODELLING OF ENERGY TRANSITION IN RURAL AND URBAN SYSTEMS

M. Freunek Müller, M. Kubli, S. Ulli-Beer

Zurich University of Applied Sciences, Technoparkstrasse 2, 8406 Winterthur, Switzerland

ABSTRACT

The current energy transition towards a rising share of fluctuating and decentrally installed renewable power has introduced new challenges to the modelling of national and regional energy supply systems. More technologies are involved than in centrally designed energy systems, and the physical potential strongly depends on regional context factors. Furthermore, nontechnical factors such as social, economic, and legislative settings, may limit solutions that are technically feasible, and the management of multiple actors with varying interests at the local and national level is required. Empirical studies show the relevance of nontechnical factors, such as delays in the approval and installation of power plants, due to missing acceptance and knowledge [1]. Modelling and scenario analyses tools have a great potential to support such complex decision and management tasks. However, the available modelling and scenario analyses tools are mostly not suited to the needs of the local stakeholders managing the transition of their local energy system. The required simulation time horizon is in the range of decades due to the long planning, construction, and life times of the energy infrastructure, which hinders an intuitive understanding of the system. Additionally, the communication of models of this size and complexity is a barrier for the energy transition [1], as stakeholders in a decentrally organized energy system have very heterogeneous backgrounds, and cannot be expected to have a detailed system understanding. Current models of energy systems are bottom-up or hybrid models, thus often bound to the regions they have been developed for. A simulation model for the transition management of regional energy systems should cover the technical system within its socioeconomic and legal boundaries, and be accessible and comprehensible on the same time. This paper provides a detailed discussion of the available energy system models for Switzerland. Exemplary effects of social and legislative issues are demonstrated. We present the participative modelling environment TREES (Transition of Regional Energy Systems) that consists of a generic interdisciplinary model which is customizable to the specific application case.

Keywords: Urban simulation, modelling, energy transition, interdisciplinary

INTRODUCTION

Existing simulation environments of energy supply systems are based on physical and economic models. Depending on the application scenario, the models are optimized for technical feasibility, least cost scenarios or maximum welfare. The current transition towards energy supply systems with increasing share of fluctuating power and decentrally installed renewable generators increases the required complexity of applied models, and the rising importance of nontechnical factors introduces new challenges to their design. The energy systems to be modelled consist of more technologies than centrally designed energy systems and involve various decisions at the local and national level. Their physical potential strongly depends on regional factors. Local and (inter-)national social, economic, and legislative settings often limit solutions that would be feasible from a technical point of view. Examples of such nontechnical factors are delays in the approval and installation of power plants due to missing acceptance and knowledge [1]. Empirical studies showed both a technology specific social acceptance and an increased probability of acceptance for existing experience with the technology [1, 2]. Such factors have not yet been added to the classical physical-economical models, which reduces their predictive value. The available research on the development of regional energy systems includes simulation models and, concerning sociotechnical issues, descriptive studies with few empirical data.

This work provides an overview of the state the art of modelling and the current research on nontechnical factors for the development of regional energy system with a special focus on Switzerland. The paper is structured as follows: First, existing general modelling approaches and the available models for Switzerland are presented. The section closes with a discussion of required model extensions following from socio-economic research. In the following part, the interdisciplinary model Transition of Regional Energy System TREES is presented. Finally, an outlook on further research is given.

MODELLING APPROACHES FOR ENERGY SYSTEMS

Energy System Simulation Models

The basic approaches of energy system models can be divided into bottom-up and top-down models. Bottom-up models typically provide a high level of detail in the technical and physical model parts and sometimes their economic properties, such as technology specific interest rates or sectorial demand. Many models include data for the development of technologies concerning their cost and efficiency. Figure 1 depicts the main components of state of the art bottom-up energy system models.

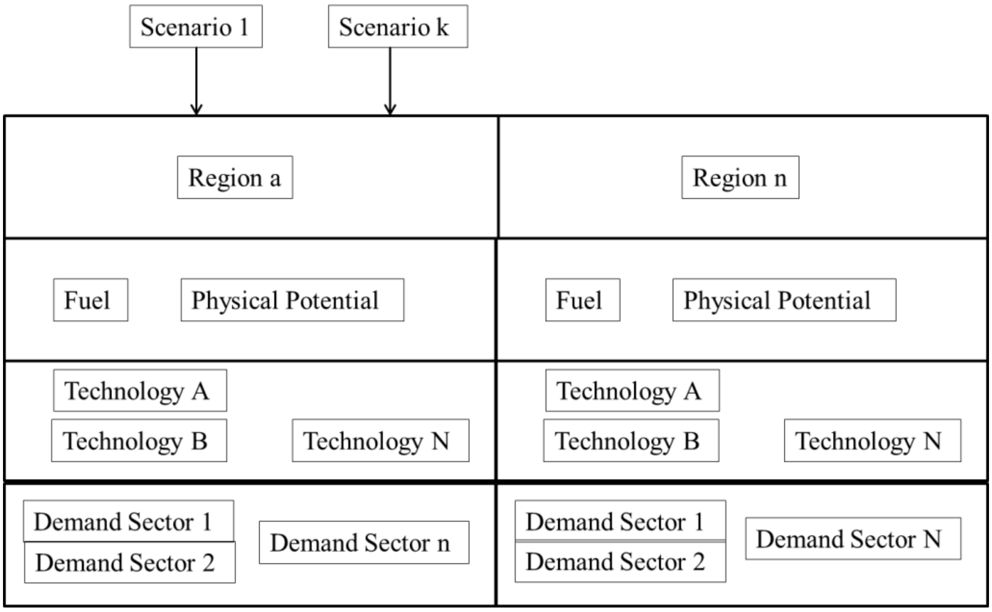

Figure 1: Typical components of bottom-up models for energy systems.

There are two main optimization directions for the bottom-up energy models: Cost and energy supply. The cost optimization models often are based on the economic concept of partial equilibrium models. Here, economic scenarios are modelled as a market, which is limited to the energy market. Equilibrium within this market is reached, when demand equals supply. The price within these models is depending on the demand. The aim of this approach is to assess the policies for a certain energy supply at lowest cost. To that aim, first the model is simulated without policy scenarios and then with possible political constraints. A very popular example is the *MARKet ALlocation model MARKAL* and its successor, *The Integrated MARKAL-EFOM System TIMES* [3]. Technologies are included from mining over energy conversion to transport for the whole world, which is aggregated to main areas. The demand side covers the domestic and industrial sectors being represented to varying levels of detail. The system dynamic model *Prospective Outlook on Long-term Energy Systems POLES*, a partially equilibrium model with endogenous price models, is another example of this model group [4]. In its structure, *POLES* is similar to the *TIMES* family. The Regional Energy Deployment System model ReEds represents a detailed, GIS-based bottom-up model of the US energy system [5].

The top-down approach provides the macroeconomic view and thus more detail of the economic behavior and system. Top-down models can be separated into two approaches: Computational General Equilibrium (CGE) Models and econometric models based on statistical analysis of historical data, such as linear regression. In CGE models, market equilibrium between demand and supply is calculated from mathematical optimization methods including detailed model of price building and many detailed sectors. As bottom-up models usually include technical models with very simplified financial assumptions, and top-down models include economic mechanisms, some approaches try to combine both [6].

Energy System Models for Switzerland

The available energy system simulation models for Switzerland are mainly bottom-up models focussing on technical and economic aspects. Kannan et. al. developed the *TIMES* model for Switzerland *Swiss TIMES Electricity Model STEM-E*, which models a single region (Switzerland) with approximated models of four neighbouring electricity markets [7]. The follower model *CROSSTEM* includes a more detailed model of foreign policies and their influence on the Swiss electricity market [8]. The overall simulations will be combined with energy system models including heat, storage and mobility in the European environment. The most detailed model of the Swiss energy system, the *Energieperspektiven* with thousands of pages of documentation has been developed by Prognos for the Swiss *Energiestrategie 2050* [9]. Their model is bottom-up with linear optimization and detailed descriptions of cohorts of existing infrastructure, buildings, electrical devices, vehicles, power plants and population based on real data.

Within the 2014 founded Swiss Competence Centers of Energy Research, various modelling activities have been started, and a broad coverage of all relevant technical systems can be expected in the near future. Again, the interdisciplinary models amongst these models focus on technical and economic aspects. For example, the University of Basel presented a bottom-up electricity market model for Switzerland, *Swissmod*, which takes into account the transmission structures, the hydropowered electric supply and the European electricity markets [10]. There are two groups with technical-economic models at ETH: The RESEC group continues its research with their dynamic general equilibrium model with endogenous growth *CITE* (*Computable Induced Technical change and Energy*). A hybrid model consisting of a CGE and a dispatch model is developed at CEPE.

On a local level, energy planning is often done by energy consultants and engineering offices. In this field, the balance sheet tool for Energy regions and the Swiss program *EcoSpeed* are used [11,12]. *EcoSpeed* is a bottom-up energy balancing tool for domestic, transport, industrial and infrastructural demand as well as production. Local potential can be optimized, and scenarios can be calculated. A common bottom-up tool in technical energy planning is the Danish program *Energyplan* [13].

Limitations of existing approaches

The energy transition includes a transition of the energy infrastructure towards a smart grid including decentral and potentially off-grid power structures, that are coupled via communication technologies. New institutions (e.g. standards, pricing mechanisms, regulations etc.) organizations and business models are also required to form secure and efficient smart energy systems. With the increasing level of realization of these new energy systems the nontechnical aspects, such as legal or socioeconomic factors, gain importance. Furthermore, the different actors, their motivations and the interactions between them need to be better understood also in their long term development. This is important since the challenge for practitioners involved in energy transition tasks is to overcome system failure [14] and to enhance their steering capacity in order to achieve policy objectives within acceptable social, economic and environmental limits [15]. This steering challenge is addressed by scientific frameworks of socio-technical transitions [16]. Researchers have applied appreciative theory and narratives to describe path dependency, path creation and circular causation in transitions of energy systems. But causal modeling and simulation frameworks are often missing, for regional settings, in particular. In addition, available research often addresses isolated topics [17]. For example, there has been no systematic approach on the interactions between consumers, grid operators, prosumers, and utilities and the effect of different technical, economic and regulatory grid operation models, although grid operators need to handle the fact, that their traditional business models already begin to fail. A descriptive study has been done by Meeus und Saguan on the often contradictory motivations of utilities and grid operators for three European case regions [18]. Agrell et. al. suggested as a results of their macroeconomic model that due to asymmetric information the reorganization of grid structures should be assigned to the grid operators [19]. However, there has been no systematic modeling approach yet, that takes into account all relevant disciplines. The same is valid for the research on social acceptance and regional installation rates of renewable technologies which is mainly descriptive and in few cases based on surveys, but always part of isolated studies [20, 21].

METHOD

The modelling environment Transition of Regional Energy Systems TREES addresses the challenges outlined above. It consists of a generic model which is customizable to the specific case. Figure 2 shows the settings and definition of boundaries within TREES. Data for exogenous variables are obtained from technical studies, national offices, and climate simulation models (METEONORM). TREES is realized as system dynamics model, as the visual approach enables a quick identification of main causal dependencies (causal loops or feedback processes), and provides an overall system overview as well as an understanding of the system behavior. In addition, scenarios, policies and actor specific strategies can be analyzed and evaluated from different perspectives and development paths. There are four main development priorities that are to be balanced: economy, acceptance of technology, ecology, and security of supply depending also on the degree of autarky or share of renewable energies.

In order to meet the regional boundaries and case specific demand, TREES consists of a base model, which is modified according to the case specific demand in the required level of detail. Figure 3 shows the modelling process. The base model TREES is built on available public data from national sources, the climate simulation program METEONORM, and results from the other SCCER research groups. In a workshop with partners from the specific case and experts, case specific scenarios, variables of analysis and system boundaries are identified.

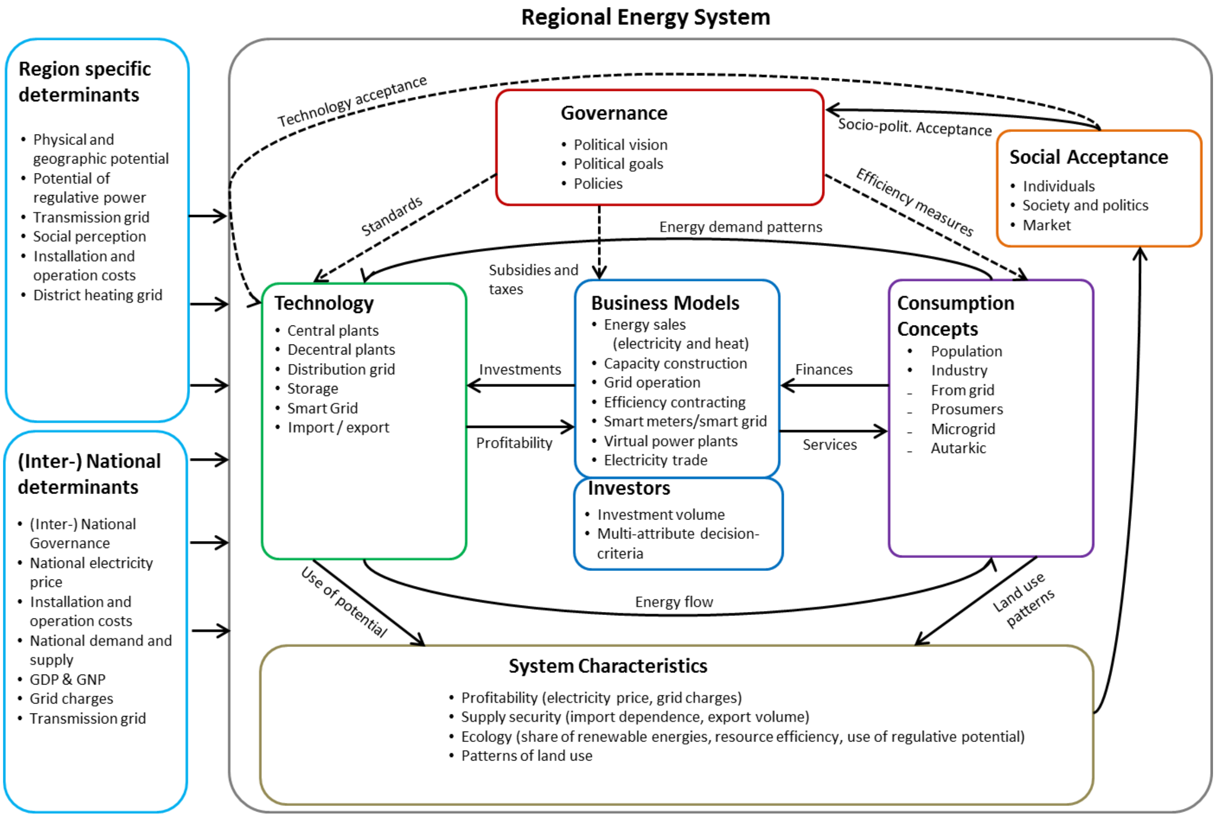

Fig. 2: (Inter-)national and region specific settings and boundaries as well as main interactions and variables in TREES.

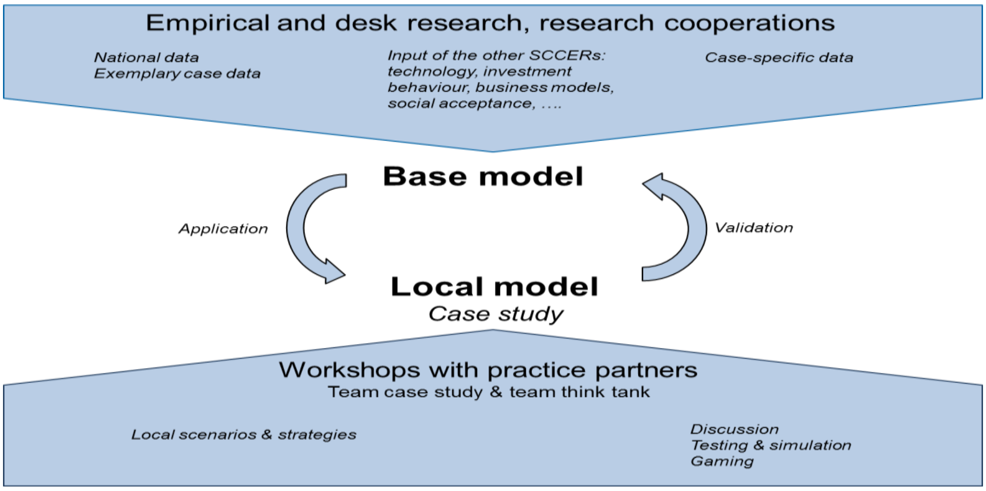

Fig.5: Modelling and data flow in the TREES model.

Besides the model specification, the aim of this participative approach is to include and identify relevant local actors in a very early stage, and to enhance their common system understanding in order to develop feasible strategies close to the real settings with its specific conditions. Based on the workshop results, TREES is adapted accordingly using additional case data. In the final step, simulations and sensitivity tests are performed; typical transition pathways, and robust strategies and policies are identified.

The main scope and implementation is its use as a strategy formation tool for planners of regional energy systems in a complex and uncertain environment. Its users are enabled to test "What if..''-scenarios and develop a sufficient system understanding. In order to allow for analysis of long term developments and also to be compliant with the Swiss *Energieperspektiven*, the time horizon ranges from 2000-2050.

The planned validation of TREES includes usage of historical data. Currently, there are few data and models available for the nontechnical variables or relations. Here, data are gathered from own research and research cooperation in order to quantify assumed correlations or functions.

CONCLUSION

An interdisciplinary modeling environment for the transition of regional energy systems TREES has been presented. With this model, relevant stakeholders can be involved at the earliest stage of project planning, and sustainable, realistic local energy systems can be developed. While the final design of the identified technical solution will in most cases require further detailed modeling with technical simulation tools, TREES assists in the task of handling a complex system with many uncertainties and individual constraints, and in identifying robust transition strategies for local energy systems.

REFERENCES

1. Federal Office of Energy: Delays of projects for current production from renewable energies [German], Bern, Aug. 2013.
2. C. Wunderlich: Acceptance and public participation of renewable energies [German]. Renews Spezial 60, November 2012.
3. R. Loulou, U. Remme, A. Kanudia, A. Lehtila, G. Goldstein: Documentation for the TIMES Model, PART I, ETSAP, April 2005.
4. B. Schade, A sensitivity analysis to investigate the impacts of oil and gas resources on the energy market, No. 23800126. EcoMod., 2008.
5. Short, W; et al., Regional Energy Deployment System (ReEDS), Technical Report NREL/TP-6A20-46534, 2011.
6. S. Rausch, M. Mowers: Distributional and efficiency impacts of clean and renewable energy standards for electricity, Resource and Energy Economics, Elsevier 36(2), 556-585, 2014.
7. R. Kannan, H. Turton, H., E. Group: The Swiss TIMES Electricity Model (STEM-E) Updates to the model input data and assumptions, November 2012.
8. R. Pattupara, R. Kannan: Exploring uncertainties in CCS – De-carbonization of the power sector & country-wise opportunities, IAEE European Energy Conference, Rome, Italy, 2014.
9. A. Kirchner, et al.: Energy Perspectives for Switzerland until 2050 [German], Prognos AG, Basel, 2012.
10. I. Schlecht, H. Weigt: Swissmod – A Model of the Swiss Electricity Market, 2014.
11. http://www.energie-region.ch/de/bilanzierungs-tool/, accessed 2015/04/29.
12. https://www.ecospeed.ch, accessed 2015/04/29.
13. H. Lund, A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, D. Connolly: From electricity smart grids to smart energy systems – A market operation based approach and understanding. *Energy*, *42*(1), 96–102, 2012.
14. R. Gustafsson, R., E. Autio: A failure trichotomy in knowledge exploration and exploitation. Research Policy, 40(6), 819–831, 2011.
15. Calvert, K., Pearce, J. M., & Mabee, W. E. (2013). Toward renewable energy geo-information infrastructures: Applications of GIScience and remote sensing that build institutional capacity. Renewable and Sustainable Energy Reviews
16. F. W. Geels, M. P. Hekkert, S. Jacobsson; The dynamics of sustainable innovation journeys, Taylor & Francis, 2008.
17. E. C. Ricci: Smart-Grids and Climate Change. Consumer adoption of smart energy behaviour: a system dynamics approach to evaluate the mitigation potential. Nota di Lavoro 71.2013. Milan, Italy: Fondazione Eni Enrico Mattei, 2013.
18. L. Meeus, M. Saguan, Innovating grid regulation to regulate grid innovation: From the Orkney Isles to Kriegers Flak via Italy, Renewable Energy 36, 2011.
19. P. J. Agrell, Smart Grid Investments, regulation and organization. Energy Policy 52, 2013.
20. N.M.A. Huijts: Sustainable energy technology acceptance: A psychological perspective. PhD Thesis, Delft University of Technology, 2013.
21. G. Walker, B. Evans, P. Devine-Wright, S. Hunter, H. Fay: Harnessing community energies: explaining community based localism in renewable energy policy in the UK. Global Environmental Politics, 7 (2). pp. 64-82, 2007.