Helmholtz Centre for
Environmental Research – UFZ
Permoserstraße 15
04318 Leipzig I Germany
www.ufz.de

Thomas Lauf | Economic Analysis of Sustainable Spatial Allocations of Energy Systems...

PHD DISSERTATION 4|2017

ISSN 1860-0387

PHD DISSERTATION **4|2017**
Helmholtz Centre for Environmental Research – UFZ
Department of Economics

Thomas Lauf

Economic Analysis of Sustainable Spatial Allocations of Energy Systems – A Theoretical Examination and an Agent-Based Model of Renewable Energy Systems

4|2017

HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ

UNIVERSITÄT LEIPZIG

Economic Analysis of Sustainable Spatial Allocations of Energy Systems

A Theoretical Examination and an Agent-Based Model of Renewable Energy Systems

Dissertation for the degree of Doctor of Political Sciences

(Dr.rer.pol.)

Leipzig University

Department of Economics / Institutional Environmental Economics

Submitted and defended by

Dipl.-Geogr. Thomas Lauf

from Wernigerode

Completion of the PhD examination procedure: 17 May 2017

Supervisors: Prof. Dr. Erik Gawel

Prof. Dr. Karin Frank

Leipzig 2017

Abstract

The question how a least-cost spatial allocation of sustainable electricity infrastructure may look like using different decision-making procedures (markets, different kinds of land-use and grid regulations) has not yet been analysed explicitly. We measure the sustainability of emerging energy landscapes providing power from renewable energy sources (RES) by an overall welfare function also comprising all kinds of space-related disutilities, i.e. spatial externalities - be they site-specific or related to the distance to a residential area (*consumer centre*).

The presented agent-based model (ABM) concept aims at assessing different policy scenarios to govern the land-use for energetic purposes under the constraint of ensuring the electricity supply for a virtual landscape with RES. To derive *optimal* spatial allocation an agent-based modelling approach is implemented, which includes a virtual landscape, three settlements as demand centres and profit-oriented producers of renewable power. For the design of the electricity grid and the calculation of grid-related reinforcement costs a load-flow model is applied, being also able to map grid externalities during the RES expansion in space.

The model allows RES producers to choose profit-maximising cells for plant installations until the given demand for power of the virtual landscape is met. Different policy scenarios allocate particular costs to agents (e.g. grid reinforcement costs, spatial externalities) or restrict the land-use with respect to ecological or social restraints. Furthermore, consumer centres have the possibility to follow own particular regional strategies, to increase their individual benefit. The overall efficiency of allocation (total cost level) as well as the distributional fairness (regional net costs) are evaluated for the policy scenarios and the regional strategies.

Danksagung / Acknowledgement

An dieser Stelle möchte ich mich ganz herzlich bei allen Personen bedanken, die zum Gelingen dieser Arbeit beigetragen haben. Mein besonderer Dank gilt meinen Betreuern Prof. Dr. Erik Gawel und Prof. Dr. Karin Frank am Helmholtz-Zentrum für Umweltforschung (UFZ) in Leipzig, die mich durch Ihre fachliche Kompetenz und Ihre strukturierte Herangehensweise unterstützt haben.

Des Weiteren möchte ich mich bei der Energiegruppe im UFZ Department Ökonomie, bestehend aus den aktuellen Mitgliedern Prof. Erik Gawel, Christian Klassert, Klaas Korte, Dr. Paul Lehmann, Dr. Nele Lienhoop, Henning Nolzen, Dr. Alexandra Purkus, Dr. Sebastian Strunz und den ehemaligen Mitgliedern Johann Singer und Katharina Witte, bedanken. Die konstruktiven Hinweise und fachlichen Diskussionen innerhalb dieser Gruppe haben entscheidend zum Gelingen der Arbeit, insbesondere in Bezug auf ökonomische Fragestellungen, beigetragen. Mein Dank geht auch an Dr. Carsten Buchmann, Gunnar Dreßler, Dr. Jürgen Groeneveld, Cheng Guo, Christian Klassert, Dr. Birgit Müller, Henning Nolzen, Nadine Pannicke, Veronkika Razykowa, Jule Schulze, Dr. Nina Schwarz und Dr. Hanna Weise, Mitglieder des *Journal Clubs* aus den Departments Ökosystemanalyse, Landschaftsökologie und Ökonomie. Die entspannten und zugleich konstruktiven Diskussionen innerhalb dieser Gruppe haben meinen Horizont in Bezug auf agentenbasierte Modellierung maßgeblich erweitert. Zudem möchte ich allen weiteren Mitgliedern des Departments Ökonomie danken, die durch Ihre herzliche Art den Promotionsalltag erleichtert haben. Besonders hervorzuheben sind dabei natürlich meine Zimmerkollegen Nils Droste und Nadine Pannicke, sowie Michael Peichl und Bartosz Bartkowski als Leidensgenossen auf dem steinigen Weg zum Promotionsglück.

Herzlichen Dank auch an alle Freunde und Familienmitglieder, die sich meine fachspezifischen Probleme anhören mussten und mich stets motiviert haben. Mein besonder Dank gilt hierbei meiner Anne, die sich die Mühe gemacht hat, die Arbeit redaktionell zu überarbeiten, mir viel Mut zugesprochen hat und dabei immer an mich geglaubt hat.

Content

3 The model evaluation 41

4 The efficiency and fairness impact of policies 57

5 The role of the regions - Lessons from the cooperative game theory and the ABM 91

List of figures

List of tables

List of abbreviations

ABM	Agent based model
BAU	Business as usual
BImSchG	Bundesimmissionsschutzgesetz (Federal Pollution Control Act)
BMU	Bundesumweltministerium (Federal Environment Ministry)
BNatSchG	Bundesnaturschutzgesetz (Federal act for the protection of Nature)
DWD	Deutscher Wetterdienst (German weather service)
EEG	Erneuerbares-Energien-Gesetz (Renewable energy source act)
FIT	Feed in tariffs
GAM	Generalised additive models
GWh	Gigawatt hour
LEP	Locational electricity pricing
LMP	Locational marginal pricing
LNP	Locational network pricing
NIMBY	Not in my backyard
OLS	Ordinary least squares
RES	Renewable energy sources
ROG	Raumordnungsgesetz (Federal planning act)
TWh	Terawatt hour

Chapter 1

Introduction

1 Introduction

1.1 The spatial allocation issue of the energy system

The German Federal government's energy concept, adopted in 2010 and emended in 2011 (BMU/BMWi 2010/11), aims at covering 80% of the gross power requirement in Germany by renewable energies till 2050. Therefore, the hitherto mainly centralized energy system, that primarily consists of large-size conventional power plants fuelled by nuclear, hard coal, lignite coal or natural gas, should be transformed in a more decentralized system that would be dominated by renewable energy sources (RES) like wind, solar, hydro and biomass. Brücher (2009) defines this transformation process as a shift from a conventional power plant dominated energy system, which generates the energy for the space, to an energy system dominated by RES, which gets its energy from the space. Bosch (2011) clarifies that concept with statements about the energy production and the amount of space needed by the different RES. He points out that the production of one GWh in Germany demands 10.2 ha for an average Biogas plant, 5.7 ha for windmills and 4.4 ha for photovoltaic cells. Although these numbers are only represented for some types of plants, it illustrates that a continuing expansion of RES leads to a struggle of space with other land uses.

As a consequence of the high spatial demand, new forms of *energy landscapes* emerge and particularly the grid infrastructure has to be adjusted to the new *spatial needs* of RES, under the restriction of a limited available space and various competing spatial interests stemming from economic, social and ecological land-uses. The term *energy landscape* describes the use of a defined area for the purpose of energy production, distribution or exploitation. Blaschke et al. (2013) illustrate common concepts associated with the approach and establish a link between physics-based views on energy commodities and their spatial footprints on the one hand, and the *energy landscape* concept and how people think about geographic space on the other hand.

Under the current energy policy setting in Germany with virtually guaranteed revenues due to feed-in tariffs and additional market premiums for RES (EEG 2014), the producers' decision where to locate RES infrastructures, is dominated, besides the distance to the closest grid connection point or the relief of the location, by natural locational factors (e.g. wind conditions, solar radiation) unless there are land-use restrictions for plant installations due to protection areas, settlements or other infrastructures. Accordingly, wind conditions and solar radiations are important factors in a multi-criteria site assessment of possible investors.

But simultaneously, it is important to harmonize the newly installed RES capacity with the existing grid infrastructure. Hence, an increasing spatial mismatch between the demand (as in the south and west of Germany) and the supply of electricity (as in the north and east of Germany) can lead to higher grid reinforcement costs because of the growing risk of reaching critical grid capacities (Nolden et al. 2013) which can lead to a temporal shutdown of renewable capacities if the electricity production exceeds the intake capacity of the grid system. Many studies deal with the topic of the grid infrastructure as a bottle neck for the energy transition in Germany (CONSENTEC 2008; DENA 2010; AGORA 2013) and additionally Barth et al. (2008) have shown that the distribution of RES integration costs, like the distribution of grid reinforcement costs among the electricity market actors, is an important issue for the transformation process of the electricity system as well.

Likewise social and ecological externalities of RES infrastructures as part of newly emerging *energy landscapes* have to be considered. They might be regarded as less important than externalities from the conventional electricity production (climate change, radiation), but the decentralized regional approach of RES power supply evokes new spatial disutilities (Meyerhoff et al. 2010) due to RES emissions or landscape aspects. On the other hand regions may benefit from RES installations through locally added values via taxes, local production and employment due to local maintenance of projects involving RES (Hirschl et al. 2010; BMVBS 2013). Consequently, the existence of regional RES externalities and benefits leads to a trade-off when it comes to new RES installations within a region.

In an overall economic consideration we have to face the spatial allocation problem of a sustainable electricity infrastructure. Therefore, it is not enough to focus on the energetic potential of RES and their impact for the supply and grid infrastructure, also societal and ecological impacts beside agents or regions preferences have to be considered to identify an allocation rule which leads to a least-cost spatial allocation.

1.2 The concept of spatial externalities

The importance of space has been underestimated in standard economics for a long time after the outstanding work by Thünen (1875) and Weber (1909) more than 100 years ago. With the conceptual framework of the new economic geography (Krugman 1999; Fujita et al. 2001) spatial effects have been reintroduced into the field, associated with terms like location, spatial interaction and spatial externalities (Anselin 2003).

Spatial externalities, which describe utility consequences for an agent *A* due to the production or consumption decision of an agent *B*, can be positive or negative. In terms of RES we will focus on the negative aspects of new RES installations. Accordingly, the so called NIMBY-(*not in my backyard*)-problem has to be taken into account. A local cost surplus can arise due to the installation of new infrastructure (generation, distribution, storage), which has a global positive net utility by definition, but can lead to negative external spatial costs. Typical examples in context of RES are the negative aesthetic impact of windmills and grid infrastructure, the odour emissions of biogas plants and the industrialization of the landscape by photovoltaic cells.

Different disciplines attempt to explain the drivers of the NIMBY phenomenon from their point of view. On an individual basis it is possible to distinguish between an economic and psychological perspective to examine the reasons of rejection of infrastructure developments. The economic view shapes it as a problem of arising externalities (Frey and Oberholzer-Gee 1997; Groothuis et al. 2008). Wolsink (2007) and Bosch (2012) have figured out that the land use type, on which the development takes place, has an important impact on the level of local acceptance. Wolsink (2007) proved this hypothesis in the Wadden region in the Netherlands and came to the result that the acceptance is significantly higher if a development takes place in an old industrial area instead of sensible nature or recreation areas. Beside the type of the landscape, the distance to the next settlements plays an important role, too. An overview on the discussion is given by van der Horst (2007). Regarding several discrete choice experiments, individuals seem to prefer larger distances to wind turbines (Meyerhoff, Ohl et al. 2010), which supports the hypothesis of the influence of the distance between a wind mill and a settlement. But it doesn´t exist consents about the shape of the influence distance curve. Differences in the planning participation, distributive aspects (Jobert 2007; Devine-Wright 2011), locally added value (George et al. 2009; Kosfeld 2011) and the significance of the land use type overlap the problem. In the following we define all NIMBY related RES externalities as societal externalities.

During the transformation process of the energy system negative ecological consequences for the environment also have to be taken into account. Of course they are not of the same extent in comparison to the impact of a conventional energy system, but because of the more decentralized production structure of RES, the spatial externalities are of high local significance. For example, an increase of bird and bat mortality risks due to wind mill instalments have been broadly discussed in the literature (Kunz et al. 2007; Kikuchi 2008). The associated infrastructure like roads and transmission lines can have a negative ecological impact as well as the fragmentation of the landscape (Kuvlesky et al. 2007). These issues can be addressed in risk maps. Bright et al. (2008) created for example a map of bird sensitivities for wind farms in Scotland. If areas with high mortality or fragmentation risk are identified, these areas can be restricted for further wind power developments during the planning process.

Hastik et al. (2015) provide an overview of typical spatial related ecological impacts of RES. The findings have been additionally related to the ecosystem service (ES) perspective which allows the estimation of the RES impacts with the help of the ES classification which includes supporting services, provisioning services, regulating services and cultural services. Furthermore, the connection to the spatial dimension of the impact is given within the study. Due to the given systematic we notice that all RES have an impact on at least one ES classification component. But the spatial context and the general strength of the effect differ among the different technologies. Tabassum et al. (2014) list all concerns connected with wind energy. Despite an underlined environmental focus also socially relevant factors are mentioned. It can be summarized that these negative spatial externalities are site-specific and include an additional distance related perspective and have to be taken into account during an overall site assessment procedure based on a cost-benefit approach, which has to be reflected by a suitable policy mix.

1.3 Modelling approaches in the context of RES

There are already manifold model approaches dealing with techno-economic or socio-economic assessments to answer spatial related questions of allocating RES plants. For example several multi-criteria site assessment models have been developed (Plata 2008; Schradinger 2008; Drechsler 2011; Langendörfer 2012; Silz-Szkliniarz 2013). All models have a static examination of the general RES potential in a certain region under a current policy regime in common. Because of these model properties they are a powerful tool for regional land use decision takers. Nevertheless they are inappropriate for an overall energy system consideration, due to their exclusion of important system components like the grid infrastructure or certain spatial externalities.

Further options to gain insights about the integration of RES in the existing energy system are complex integrated assessment models. These models focus on the techno-economic interplay of certain components of the energy system.

Models of the field of power system engineering (Gross 2006; Remme 2006; Holttinen et al. 2011; Haller et al. 2012) for example seek to give precise scenario based estimations of additional integration costs of new RES installations. They provide a good technical representation while focussing on short term consequences for residual loads and grids. More economic based model approaches (Joskow 2011; Mills and Wiser 2012; Nicolosi 2012) focus on the marginal long term costs via a determination of an optimal welfare generation capacity amount per technology. Accordingly, considered short and long term system trade-offs will be taken into account whereas the technical system representation is typically simplified. Nevertheless both frameworks neglect spatial externalities and the embeddedness of power provision into landscapes.

In contrast, we focus on a spatially explicit virtual heterogenic landscape and the task to *optimally* allocate RES infrastructure by maximizing the overall welfare by taking spatial disutility into account. To determine the least-cost solution, spatially independent costs for production, back-up capacities, transportation, plus social and ecological externalities have to be considered under different decision making procedures for the spatial infrastructure allocation (markets, regulations). Accordingly, the spatial-oriented perspective of economic interpretations in context of RES, which typically focusses on geographical resource variations and distribution-related costs, will be expanded with an additional consideration of site-specific spatial externalities. But perspectives such as energy efficiency that may decrease the overall energy demand, as well as storage technologies that can reduce back-up capacities, are not considered here for reasons of simplicity.

Apart from efficiency patterns, the role of interregional distribution effects has to be analysed. Regions play an important role for the spatial allocation since they have to provide suitable space for infrastructure units (plants, transmission lines) or have to pay their local costs respectively. The amount of the net costs, which a region has to bear in order to contribute to a spatially optimal power provision, describes the distributional fairness of spatial RES allocation.

Accordingly, the impacts of different policies (market-based or planning instruments) on the total cost and its regional distribution need to be examined.

To answer the question how an optimal spatial RES allocation might look like and what kind of regulation is needed to establish such an *energy landscape* pattern, a conceptual agent-based model (ABM) is implemented. These kinds of models attract growing attention in the scientific community as a useful modelling tool for spatial issues, autonomous decision behaviour, and policy impacts. Heppenstall et al. (2012) provide an overview of ABM within geographical systems and give a broader perspective on the bottom up approach.

Yet, there already exist several ABM models with an energy-related background on a global (Chappin and Dijkema 2010) or local scale (Wittmann 2007) dealing, for example, with electricity markets (Bunn and Oliveira 2001; Krewitt 2011) or the general transition procedure within electricity systems (Ma and Nakamori 2009). However, these models either exclude spatial related issues, or focus on a particular case study without considering cross-cutting effects among regions.

In this thesis, the presented regional conceptual ABM-approach combines rational choice behaviour based on economic theory with land-use modelling originating in geography, and load flow modelling coming from electrical engineering by considering interaction between the producers, the consumers and the grid infrastructure. The approach allows the illustration of socio-economic (e.g. spatial desutilities, regional value creation) and techno-economic (e.g. grid infrastructure) aspects together in one model framework to estimate the efficiency and fairness of a sustainable energy system on a regional scale.

1.4 Structure of dissertation

After providing a general overview of the energy transition process with its corresponding spatial issues in chapter 1, the ABM will be presented in chapter 2. Besides the entities and target functions (section 2.2) and the general model procedure (section 2.3) the implemented modules will be illustrated within section 2.4. Furthermore, an overview of the evaluation functions (section 2.5) and the applied policy scenarios (section 2.6) will be given. The chapter 2 will be finalized by the applied techniques for enhancing the model plausibility in order to rule out unrealistic model behaviour in section 2.7.

In chapter 3 the basic policy scenario, which is a reflection of the market based policy situation, will be examined. Therefore the evaluation strategy will be presented, together with the applied statistical models for the evaluation of the produced Monte Carlo Simulation samples in section 3.2. Afterwards the influence of the basic parameters on the efficiency and fairness will be tested in section 3.3.

Within chapter 4 the role of policies on the overall efficiency and fairness variables will be examined and regulation based policies in form of land-use restrictions and land-use designation will be analysed in section 4.1. Accordingly, the spatial module of the ABM will be extended by additional land-use parameters, before the impact of this regulation-based land-use parameter on the central model variables will be analysed. Section 4.2 focuses on the design of market-based policies. The support scheme for renewables will be extended by a reference yield model (section 4.2.1). Then different reference yield model designs will be applied in order to test their impact on the outcomes. In the following section 4.2.2 the welfare relevant grid reinforcement cost category will be reallocated among the agents. Therefore the effect of different degrees of cost absorption will be analysed.

The role of the regions will be examined in detail in chapter 5. A cooperative game theoretical approach will be tested for further examination. Then a spatial externality avoidance and a regional economic encouragement strategy for the regions will be introduced in order to increase the individual regional net utility of the consumer centres (section 5.3). Finally the effect of these additional strategies on the efficiency and fairness will be analysed (section 5.4). The final analysis in chapter 6 evaluates the existing trade-offs between implemented policies and a regionally specific strategy application on the basis of the German Energy transition as case study.

In the last chapter 7 the ABM will be summarised and reflections on the limitation of the model approach will be given. Then further model extensions will be discussed against the background of increasing the model plausibility and model complexity.

Chapter 2

The model

2 The model

2.1 Overview

The objectives of the agent-based model are the identification and exploration of the least-cost allocation of RES power infrastructure (power plants, grids) within a virtual landscape in order to guarantee a secure supply (in sense of market clearance aspects but without taking volatile production patterns into account) of given consumers' overall electricity demand in three settlements (as regional consumer centres) under consideration of distributional aspects of regional net cost burdens. The model's target function is an overall welfare function that particularly also comprises all kinds of negative impacts of allocating RES plants and grid extensions through particular cost functions.

Via additive cost functions the model is enabled to integrate all impacts of RES power allocation on energy landscapes. Beside costs for power production and for using existing grids, spatial external costs as well as grid externalities (grid reinforcements) can be considered. In other words, the usual techno-economic business view is extended to a broader eco-socio-economic perspective by respective spatially explicit modelling and the implementations of spatial externalities. Sustainability of energy landscapes in this framework means an overall least-cost and fair allocation of RES power plants including all kinds of space-related disutility. Figure 1 provides an overview of the implemented spatial allocation criteria for RES which have been taken into account with the ABM framework.

Regarding a sustainable allocation several problems have to be discussed. Firstly, production plants have to be located and connected to the existing grid infrastructure. Secondly, a reinforcement of the existing grids system might be necessary, because of changed load flows evolved by the newly installed capacity. Finally, it is important to analyse cost distribution aspects of possible allocations. Since the overall efficiency of power provision from the energy landscape is a public good, a certain risk of freeloader behaviour exists as soon as the overall efficient allocation of RES infrastructure leads to a negative net utility within a certain region suffering from significant spatial disutility but contributing efficiently to the total power supply. Decision-makers of affected regions might tend to restrict land-use for profitable RES production sites in order to ease regional space disutility. However, also additional regional specific support might be an option for local decision-makers in order to benefit from regional economic welfare effect laid out by local RES investments. These measures might reduce overall efficiency of RES power supply and could be answered strategically by the remaining regions.

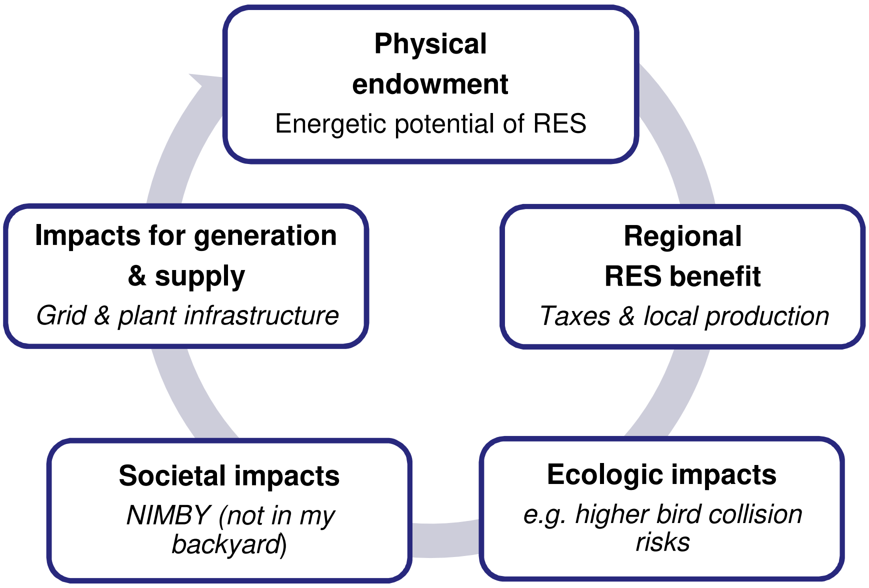


Figure 1: Considered spatial allocation criteria for RES within the ABM

The agent-based perspective allows the introduction of rational producers choosing profit-maximizing allocation sites given a certain policy regime (e.g. remuneration, land use). Furthermore, the model introduces rational *consumer entities* being affected by producers' allocation decisions. Each consumer centre can decide to implement regional land-use policies (to protect its catchment area from spatial disutility) and therefore to leave the overall optimization approach for establishing a self-sufficient region with respect to RES supply. Thus, the model will also map production coalitions of regions. Moreover, due to the possibility of introducing different market, grid and land-use regulations on different governance levels (regional or *'national'*) in the conceptual ABM, several policy scenarios will be tested regarding their overall welfare (efficiency) and the arising regional cost distribution within the virtual landscape (fairness).

The presented ABM has the objective to explicitly focus on spatial related criteria of the energy system. Temporal aspects, which overlap the complex decision process, are so far not considered. Therefore, we do not deal with volatility aspects of RES, nor storage, nor demand site management to guarantee a harmonized supply and demand.

For simplicity, we only focus on a single RES technology (say onshore wind power) with a given capacity per plant unit though neglecting any intermittency problems. The model was programmed in NetLogo (Wilensky 1999) and R (R DEVELOPMENT CORE TEAM 2013) whereby only the site assessment takes place in NetLogo. The two programs are connected via a link package developed by Thiele (2012). Furthermore, the model description has been carried out by considering key elements from the ODD protocol developed by Grimm et al. (2010).

2.2 Entities, variables and scales

The central target function of the model is the overall welfare function W of the virtual energy landscape, comprising the producer and the consumer surplus of the energy provision (PS, CS) and the space-related external disutility X emerging from land-use for RES power production and transportation.

$$W = PS + CS - X \tag{1}$$

The cumulative profits π of the N RES producers represent the producer surplus PS. The producers have to consider their business production costs C_P, which represent all arising costs during the life time of a plant, as well as the business connection grid costs C_{GC}, to connect the installed plant with the existing grid infrastructure. Business production costs include all fix and variable costs like the investment, maintenance and repair costs which are all dependent on the plant type.

$$PS = \sum_{n=1}^{N} \pi_n \tag{2}$$

The consumer surplus CS consists of three parts. Firstly, we have the positive utility due to the purchase of electricity, calculated as difference between the consumers' willingness to pay (reservation price p_{max}) and the actual (given) market price for electricity p.

Secondly, a multiplier effect m due to the regional electricity production out of RES is another part of the consumer surplus. It is defined as regional economic welfare effect because of the RES installation defined as Y^S, which for example emerges through tax revenues and job creations within maintenance companies (Hirschl et al. 2011; Kosfeld 2011). In general the local value-adding process of RES can be divided into four steps, which includes beside the construction of the plant and its corresponding components, the planning and installation process, the maintenance plus the profits of the operating company.

Thirdly, the business costs for the existing grid system C_{GE} have to be subtracted from the aforementioned terms of CS. These costs emerge if net segments of the existing grid system have to be reinforced due to load flow changes because of newly installed RES plants (Barth, Weber et al. 2008). They are dependent on the connected RES power capacity and the presented structure of the grid, the change of the typical load flow pattern in comparison to the situation with no integration of RES-E power capacity and the impact of connected RES power capacity on power quality and system stability.

$$CS = Y^D \frac{p_{max} - p}{2} + mY^S - C_{GE} \tag{3}$$

The third term X of the welfare equation is defined as the sum of external spatial costs (spatial disutility). These costs can arise due to NIMBY-related or ecological issues. Although we know that a precise spatial definition of both issues is hard to obtain, it is possible to generally divide them into a distance-related (van der Horst 2007; Eichhorn and Drechsler 2010) and a site-related cost component (Kunz, Arnett et al. 2007; Kuvlesky, Brennan et al. 2007; Wolsink 2007). In the model both are captured cumulatively via a distance- and a site-dependent external cost function. After summarizing these two functions we get the total external spatial costs, which arise because of production infrastructure X_P and distribution infrastructure X_G (i. e. grids).

$$X = X_P + X_G \tag{4}$$

The following Figure 2 resumes all introduced cost categories and points out which agent is affected in the reference case. Furthermore, we can distinguish the cost categories in a business consideration and a total economic cost consideration including all kinds of external spatial costs. External costs are imposed on the consumer centres unless explicit internalization policies are established. As the electricity demand of all consumer centres Y^D will be defined at the beginning of a model, any welfare improvement is performed via a total cost minimization.

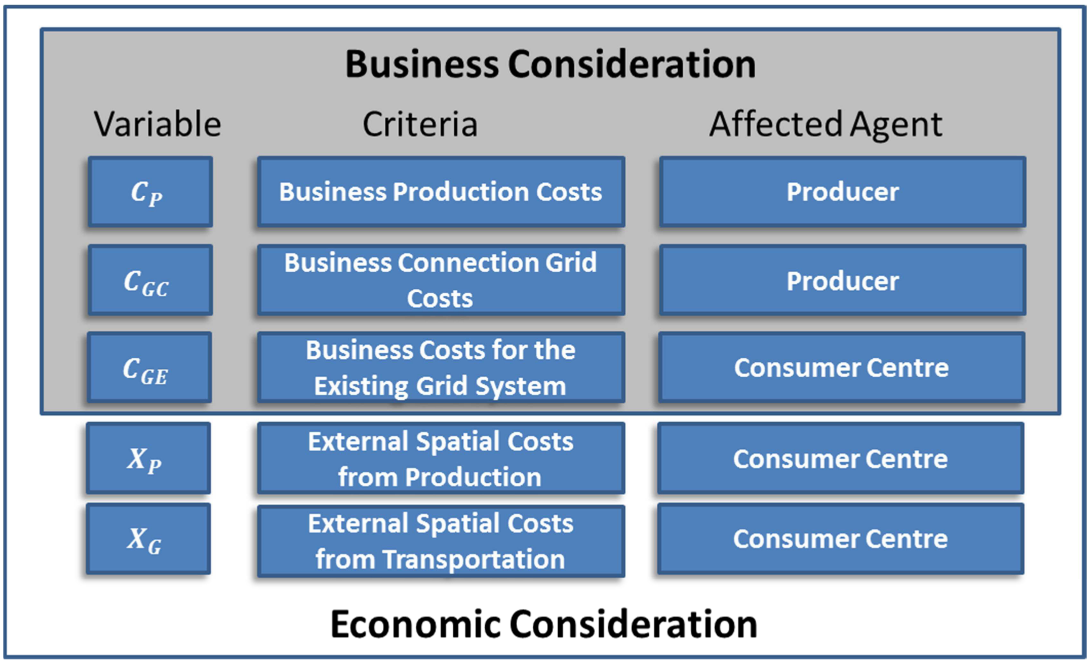
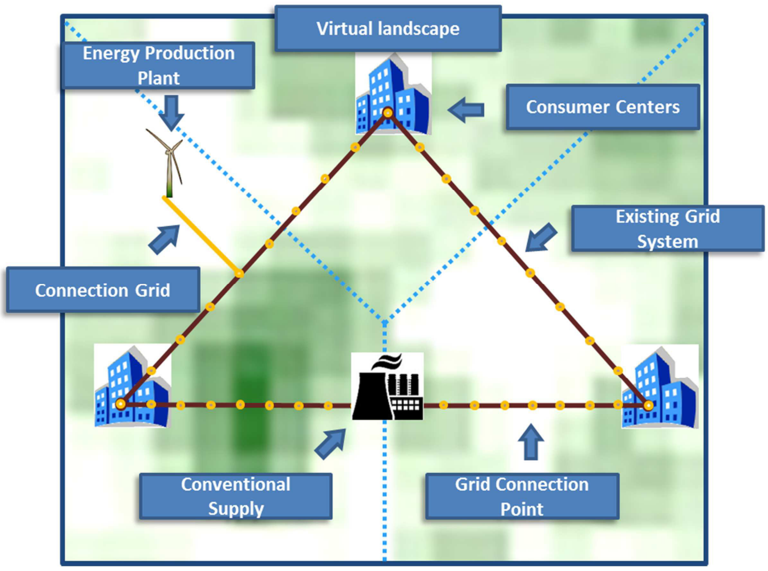


Figure 2: Defined cost categories for the spatial allocation of production and distribution infrastructure within the ABM framework

The sensibility of a site, regarding the installation of a production or distribution infrastructure, is defined as site-dependent external costs x_S. Ecologically important sites or landscapes with considerable aesthetic value suggest a high vulnerability regarding new constructions in general. Examples are the existence of breeding areas for rare bird or bat species (Kunz, Arnett et al. 2007; Kikuchi 2008) or aesthetic landscapes within a mountainous area together with important historical heritage.

The energetic yield potential and the site-dependent external costs are randomly distributed under consideration of the cell´s neighbourhood values, which can be explained due to the spatial correlation between a cell and its neighbourhood cells for wind conditions on the one hand and land use types on a regional scale on the other hand. Therefore, the maximums of h and x_S will be defined before the virtual landscape generation, to produce an interval which will be used for the random assignment of the cell values.

Figure 3 shows all relevant model entities. The three consumer centres, as illustrated above, are defined as conglomerations of households with a fixed (and equal) electricity demand Y_j^D per consumer centre. Simultaneously they act as a local administration entity with a particular manageable catchment area. As mentioned in Figure 2 they are affected by the external spatial costs that arise within their catchment area. On the contrary they benefit from the multiplier effect of the RES which also depends on the installed capacity Y_j^S within the catchment area of a consumer centre. To guarantee the security of supply in terms of market clearance (Volatility aspect are not considered within the model framework), all consumer centres are connected with each other via an existing grid infrastructure. The existing infrastructure is adapted to a conventional electricity supply from a single load point, defined as conventional supply which covers the total demand of all consumer centres at the defined starting situation $t = 0$.



Cells:
$\{i = 1, \dots, I\}$

Consumer Centers:
$\{j = 1, \dots, J\}$

Existing Grid System with Edges:
$\{e = 1, \dots, E\}$

and Vertices:
$\{v = 1, \dots, V\}$

Producer:
$\{n = 1, \dots, N\}$

Figure 3: Representation of all relevant model elements

New RES power producers in form of wind power plants have to connect themselves to the existing grid system via a grid connection point and a connection grid like it is defined in the German support mechanism (§ 5 EEG 2014). Therefore, the producer is only responsible for the plant connection to the nearest connection grid point. If the existing grid system in turn has to be reinforced, additional costs for grid expansions arise, which have to be paid by the consumer centres in the market scenario.

The actual location choice concerning new plants lies in the hand of the RES producers. They are profit oriented. In other words, producers act as rational agents following the merit order principle which means that the sites with the highest profits regarding the producer profit function will be picked first. In the basic market scenario no land-use restriction or internalization policy applies.

2.3 The model procedure

The objective of the consumer centre is to completely supply its defined energy demands out of RES, which means that a given conventional supply meeting the current demand will be incrementally substituted by a RES power supply. Accordingly, a new producer of renewables picks a site in the virtual landscape regarding his profit function during every time step. This procedure is repeated till the total RES supply within the virtual landscape is equal or higher than the total demand.

$$Y^S \geq Y^D \tag{5}$$

As mentioned earlier, the profit-oriented site assessment does not consider any catchment area boundary of the consumer centres. Producers simply maximize their profit function (6) during their site-assessment process.

$$\max_{y^s, c_n} \pi(y^s, c_n) = py^s - c_n \tag{6}$$

The profit function depends on the particular policy scenario and its intended cost categories for the producers. In the basic market scenario the producer takes the business production costs and the business connection grid costs into account, which are represented in the grey box of Figure 2.

$$c_n(c_P, c_{GC}) = c_P + c_{GC}(d_{iv}) \tag{7}$$

Since all producers use just one single plant per definition, the business production costs c_P are equal to the factor costs of the respective plant type w_{PC}.

$$c_P = w_{PC} \tag{8}$$

For the calculation of the connection grid cost the minimal distance between the plant and the next connection grid point on the existing grid system will be calculated. Afterwards, it will be multiplied by a distance related factor price.

$$c_{GC}(d_{iv}) = w_{GC} \min d_{iv} \tag{9}$$

The energetic output per plant is the result of the multiplication of the energy yield potential per cell by the performance parameter of the plant l_{PC}. Therefore, y^s represents the average amount of electric work, which is transmitted to the consumer centres via the grid system. At the beginning the performance parameter is constant due to the usage of only one wind power plant type.

$$y^s(h) = hl_{PC} \tag{10}$$

Afterwards the energetic output per plant will be remunerated, dependent on the given average price for renewable electricity. No explicit electricity power market is implemented in the model. Instead, a fixed feed-in tariff scheme for the entire landscape applies. The remuneration of RES power feeding-in (as in the German reference yield model for wind power (AGORA 2014)) may be altered in the course of more complex policy scenarios.

2.4 Sub-models

2.4.1 General model structure

The whole model has a module-based structure. In every module separated variable calculation procedures apply which can be seen as input variables for the downstream modules. Depending on the setting of the policy scenarios criteria of the site assessment procedure for the producer may change, which in turn can affect the profit function of the RES producer. Moreover, the introduction of land use regulations can influence the site availability within the virtual landscape.

Parameter combinations for the calibration and validation process of the model will be determined inside the *Setup Parameter* module. Because of the random generalized virtual landscapes multiple model runs will be necessary to enhance the robustness of the outcomes. After the definition of the scenarios and parameter settings, the actual model calculation begins. The calculation of spatial dependent variables takes place in the *Spatial Module* which calculates cell based values for every variable. At the same time, the *Grid Generation Module* runs to determine the start condition regarding the business costs for the existing grid system.

As soon as all relevant variables for the site assessment have been calculated, the producers pick their optimal sites and build RES plants. That happens in form of multi-criteria site-assessment within the *MCSA* module. Because of potential load flow changes, due to the installation of new plants, the *Grid Module* has to run after every installation to determine bottlenecks of the network and the actual arising reinforcement costs. After the final model condition has been fulfilled (i.e. meeting the overall demand by installed RES power capacities), the subsequent evaluation process starts. Figure 4 sums up the complete model structure.

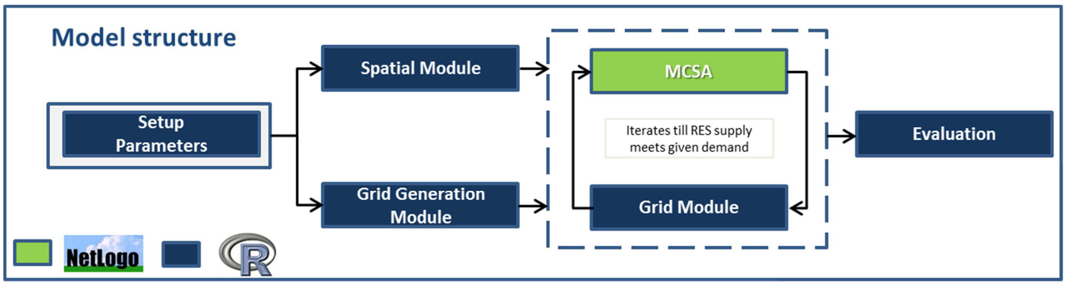
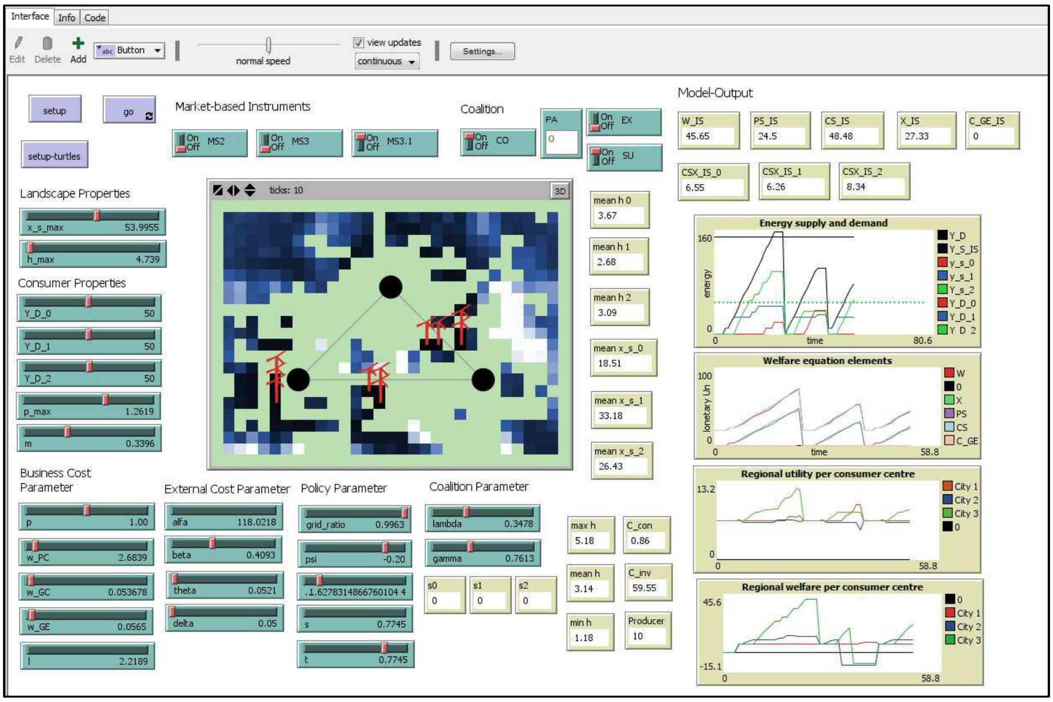


Figure 4: Overview of the complete model structure

In Figure 5 a screenshot of the NetLogo implementation is shown. Basically the screenshot can be divided in four parts. All used parameter are represented on the left sight including the lower left corner. In the middle of the figure the virtual landscape with the consumer centres and producers are shown after a completed model run. Above the virtual landscape all scenario and coalition based switches can be find and finally on the right sight different kind of evaluation plots and model outputs for the precise observation of one model run are illustrated. Netlogo and R are connected via the package *RNetlogo* developed by Thiele et. al (2012). It allows to steer Netlogo from R with specific command lines. Therefore, Netlogo serves as graphical user interface (GUI) during a model run. Due to the flexibility of R regarding statistical analysis, spatial and graph related operations all other modules are implemented within the R framework.

Beside the *RNetLogo* package additional R packages have been used within the different modules. As the model deals with raster based virtual landscape the *raster* package has been applied (Hijmans 2015). Additionally, the R package *gdistance* (van Etten 2012) for the calculation of distances and routes has been very important within the spatial module. To generate a grid system within the grid module we implemented the *igraph* package (Csardi and Nepusz 2006), which allows to generate complex graph systems existing out of edges and vertices.



PA 0

x_s_max 53.9955
h_max 4.739

Y_D_0 50
Y_D_1 50
Y_D_2 50
p_max 1.2619
m 0.3396

p 1.00
w_PC 2.6839
w_GC 0.053678
w_GE 0.0565
l 2.2189

alfa 118.0218
beta 0.4093
theta 0.0521
delta 0.05

grid_ratio 0.9963
psi -0.20
.1.6278314866760104 4
s 0.7745
t 0.7745

lambda 0.3478
gamma 0.7613
s0 0
s1 0
s2 0

mean h 0 3.67
mean h 1 2.68
mean h 2 3.09
mean x_s_0 18.51
mean x_s_1 33.18
mean x_s_2 26.43
max h 5.18
C_con 0.86
mean h 3.14
C_inv 59.55
min h 1.18
Producer 10

W_IS 45.65
PS_IS 24.5
CS_IS 48.48
X_IS 27.33
C_GE_IS 0
CSX_IS_0 6.55
CSX_IS_1 6.26
CSX_IS_2 8.34

Figure 5: Screenshot of the NetLogo implementation

2.4.2 The Spatial Analysis

All spatial related calculations, like the computation of the external spatial costs and the minimal distance for the connection grid, take place in the *Spatial Module*. Figure 6 provides an overview of external spatial costs, defined above, together with the associated raster maps. Spatial externalities affecting directly human beings (e.g. landscape aesthetics, health effects: *social external costs*) and spatial externalities affecting ecosystems with indirect impacts on human well-being (e.g. bird mortality, dissection of landscapes: *ecological external costs*) are differentiated. They may be dependent either on the distance to the consumer centres or on the site-specific ecological vulnerability:

$$x_P = x_D + x_S \tag{11}$$

The sum of the calculated distance-dependent external spatial costs x_D, and the randomly distributed site-dependent external costs x_S is the input x_P for the calculation of the external spatial costs for the production and the transportation of electricity. As land use types are often arranged in clusters, we determine a similar arrangement of the site-specific ecological vulnerability by including neighbourhood values in the distribution process of x_S.

$$x_D = \sum_{j=1}^{J} \alpha d_{ij}^{-\beta} \frac{Y_j^D}{\bar{Y}_j} \tag{12}$$

The distance-dependent external spatial costs (11) will be determined by the distance between a cell i and a consumer center j, an exogenous intensity parameter α and, a curvature parameter β within the interval $[0,1]$, which leads to an exponential decrease of the cost parameter with increasing distance. We presume that the distance-dependent external spatial costs are constant across all consumer centres. Accordingly, these costs also depend on the ratio between the electricity demand of a consumer centre Y_j^D and the average electricity demand $\bar{Y}_j$. Due to the cross-border visibility of RES plants, distance-related costs do not only arise in the consumer centre’s catchment area where the plant is situated, but have to be considered in general for all affected consumer centres. If a producer installs a RES plant on a particular cell, external spatial costs for both production and transportation of RES power arise. For the calculation of the external spatial costs for transportation, all cells which are crossed by the grid infrastructure have to be included. For that reason the least-cost path method (cf.Pinto and Keitt 2009) will be applied to find a least-cost route with regard to the external spatial costs between the cell of the RES production plant and the closest connection grid point.

$$x(x_P, x_G) = \delta(x_P + \theta x_G(x_P, d_{iv})) \tag{13}$$

In the end all resulting external costs will be aggregated (13). The parameter θ is included to determine the intensity differences between external spatial costs due to production and the transportation infrastructure. The relations between the aggregated external spatial costs and the business costs will be steered by the parameter δ.

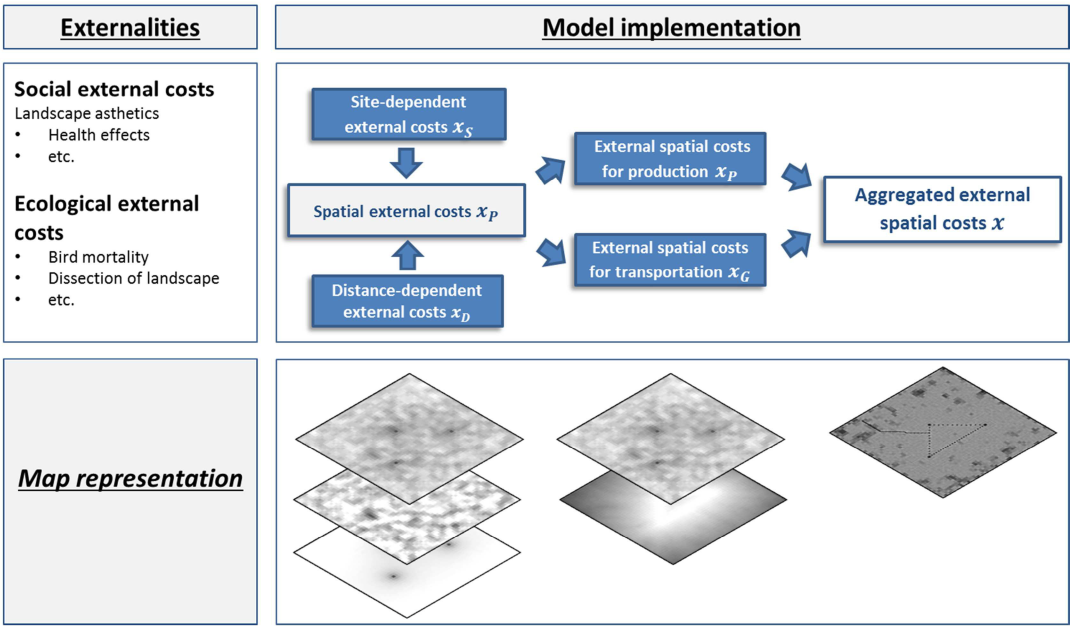


Figure 6: Calculation of the external costs including the particular raster maps

2.4.3 The Grid Module

The *Grid Module* is important for the calculation of the business costs for the existing infrastructure C_{GC} which comes into play if net segments have to be reinforced due to load flow changes because of newly installed plants. New RES capacity can be the reason for the development of bottle necks in the grid system, through the generation of a high amount of electricity, which may be larger than the actual transportable capacity of the existing grid.

For illustrating this phenomenon it is necessary to develop a simplified network approach which contains basic physical regularities. In principle, it is possible to distinguish between two load flow model approaches. The best way to simulate load flows of electricity is an iterative procedure under the consideration of active and reactive power called alternating current load flow models (AC-Model). Unfortunately, these techniques are difficult to apply due to the demanded resources. Because of the conceptual model approach a simplified version of the AC-Model, which only focuses on active power, called direct current load flow model (DC-Model), is applied for the ABM framework. During the application of both network approaches in a case study (Overbye et al. 2004) it has been shown that relevant network patterns can also be examined with a simpler DC-Model. Nolden et al. (2013) provide an overview on the common models used for techno-economic approaches. DC-Models with various extensions dominate the examination especially for policy investigations (Schweppe et al. 1987; Weigt 2006; Leuthold et al. 2008).

Because of excluding network losses, reactive power and phase angles differences it is possible to shape the problem in a linear way. If the impedance is known and the phase angles are constant, the equation of the Ohm’s law shrinks to $I = 1 / R$. In the case of our model, R is defined as distance between two connection grid points. The edge between two neighbour connection points v and $v + 1$ is defined as e. For the calculation of the load flow change within a net segment e, the feed in electricity amount of v is decisive.

$$PTDF_{ve} = \frac{\Delta y_e}{\Delta y_v} \tag{14}$$

The Power Transfer Distribution Factor (PTDF) (14) (cf. Duthaler 2007) has to be calculated for all network segments and connection grid points. As a result a PTDF-Matrix is defined. Therefore, it is possible to calculate the load flow by the summarization of all electricity feed-ins of all affected connection point.

Consumer centres with their associated demand are defined as load points. Via a composition assumption the generation (electricity production of RES plants) form any connection point has to be assigned to the different load points. The ratio between the total demand and the demand of a consumer centre determines the load flow (15).

$$Y_{jv} = \frac{Y^D{}_j}{\sum_{j=1}^{J} Y^D{}_j} Y_v \tag{15}$$

Afterwards all supplies of electrical power at any connection point to all load points for every net segment are summarized. As a result we get the load flow capacity for all net segments at the time t (16).

$$cap_e^t = \sum_{j=1}^{J} \sum_{v=1}^{V} P_{jv} PTDF_{\ ve} \tag{16}$$

If the starting capacity of the net segments at $t = 0$ is exceeded, a reinforcement of the particular net segment will be necessary to guarantee supply security. The level of the capacity exceedance is multiplied by the factor price w_{GE} and therefore, determines the business costs for the existing net segment ${C_{GE}}_e$. After summarizing all arising costs for the net segments we get the total business costs for the existing grid system C_{GE}, which have to be paid by the consumer centres dependent on the ratio between the total demand and the demand of the particular consumer centre.

$$C_{GE} = \sum_{e=1}^{E} {C_{GE}}_e = \begin{cases} w_{GE}\ (cap_e^{t=1} - cap_e^{t=0}) & if \quad cap_e^{t=1} > cap_e^{t=0} \\ 0 & else \end{cases} \tag{17}$$

Accordingly, the new capacity is the starting condition for the next time step $t = 1$. Figure 7 provides a graphical overview on the basis of two time steps. On the left hand side we see the conventional starting situation at $t = 0$ with a electricity feed-in of the total demand through one connection grid point. In picture B we see a newly constructed RES plant which feeds in electricity via a one particular connection grid point. The load flows for all net segments have to be calculated to examine possible bottle neck situations in the grid system. The conventional electricity feed-in reduces with the similar amount of the new feed-in of the constructed RES energy plant. The consumer centre demands remain equal, whereby the supply situation changes due to the simulated transition of the model´s energy system.

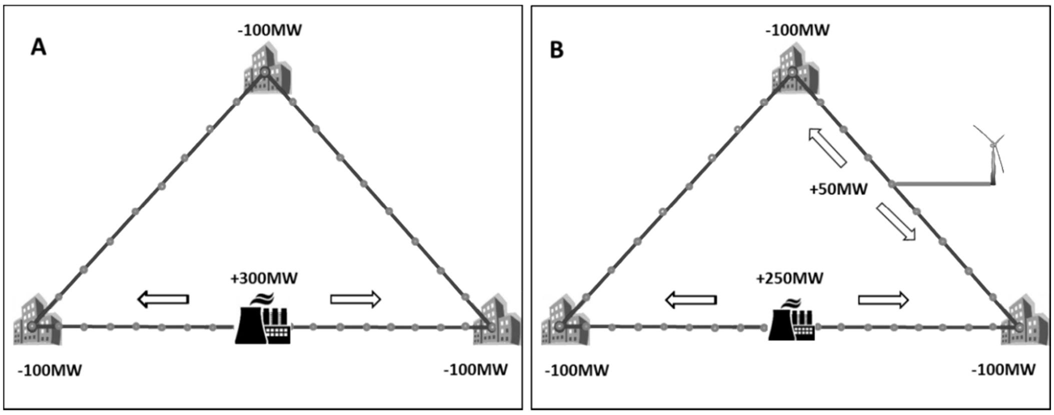


Figure 7: Representation of the load flow situation at two time steps

2.5 Evaluation equations

The performance of each policy scenario can be assessed under the aspect of efficiency and distributional fairness among the consumer centres (regions). Efficiency refers to the resulting overall welfare (1), after the transformation from a conventional to a sustainable supply is completed. A positive welfare is guaranteed if the sum of producer and consumer surplus is always higher than the external spatial costs. This condition is used for calibration of the model since otherwise RES power supply economically would not make sense provided that sustainability issues represented by spatial disutilities are relevant for the economy.

To determine the fairness of a resulting spatial allocation the regional consumer surplus, minus the respective regional spatial externalities within each region of the virtual landscape, have to be calculated. The regional net utility CSX_j per consumer centre considers the positive utility due to the purchase of electricity, the regional multiplier effect (depending on the produced electricity of the RES plants within the catchment area of the consumer centre j), the share of the business costs for the existing grid system and the regional spatial externalities (arising within the catchment area of the consumer centre j).

$$CSX_j = Y_j^D \frac{p_{max} - p}{2} + mY_j^S - C_{GE} \frac{Y_j^D}{Y^D} - \mathrm{X}_j \left(X_{G\,j}, X_{P\,j} \right) \tag{18}$$

If CSX_j increases for all consumer centers J during the RES deployment process, all regions can benefit from the transformation of the energy system and have no incentive to exit the production coalition. Consumer centres with a negative regional net utility development can be on the other side willing to leave the producer coalition (existing out of all three consumer centres), with the consequence of an autonomous electricity provision within their own region, that may lead to a general welfare decrease of the complete virtual landscape. Due to the possible differences of the electricity demands among the consumer centres and between the specific model runs, we calculate the regional net utility per demand unit to make the specific results comparable with each other and define it as regional net utility per capita.

$$csx_j = \frac{CSX_j}{Y_j^D} \tag{19}$$

Finally, the inequality among the regions is measured by an adapted and normed Gini coefficient using the resulting regional net utility. The coefficient measures statistical dispersion among units, whereas a coefficient of 0 implies perfect equality, which in our case would mean that all consumer centres have the similar regional net utility per demand. A coefficient of 1 expresses maximal inequality. As it is possible that a consumer centre has a negative regional net utility per demand after a complete model run, we use normed results for the calculation of the coefficient.

$$Gini = \left(\frac{2\sum_{i=1}^{n} icsx_{(i)}}{n\sum_{i=1}^{n} csx_{(i)}} - \frac{n+1}{n}\right)\frac{n}{n-1} \tag{20}$$

2.6 Policy scenarios

After the definition of the evaluation criteria of a single model run we have a framework to identify good spatial allocation rules for RES via different policy scenarios. A policy scenario is defined as a set of rules allocating welfare-relevant cost and benefits across actors in a particular way or a regulation which has the aim to avoid externalities. Reference case is a basic market scenario that allocates the business production costs and the business connection grid costs to the producer and all kinds of externalities to the public (consumer centres). In contrast, energy and environmental policy may reallocate costs (grid extension cost, external cost) in order to improve the overall efficiency of the power supply from the energy landscape. This can be done by different means of policy intervention (instruments).

The use of ABMs to test the influence of policy scenarios in the context of land use change and agriculture activities has already been applied by Berger (2001), Berger et al. (2006) and Happe et al. (2006). Other authors contributed ABM based policy analysis in the field of coastal ecosystem protection (Filatova et al.

2011), biological conservation (Hartig and Drechsler 2009) or biodiversity (Polhill et al. 2013). Even in the related RES field of emission trading markets (Zhang et al. 2011), ABMs are used to analyse the influence of transaction cost on a particular market-based policy.

An adequate policy design is crucial for the German energy transformation process. Therefore, it is important that the actual policy design avoids unnecessary costs and helps to guarantee public acceptance (Gawel et al. 2014). Several policy scenarios, that are associated with RES allocations, can be examined within the presented ABM framework. In general we can distinguish between a market-based and a regulation-based policy framework. Accordingly, the classical trade-off between market and planning solutions can be identified in the realm of the energy transition process.

Chapter	**Market-based**	**Regulation-based**
3	**Market I** Basic market scenario (Basic scenario)	-
4	**Market II** Reference yield model	**Regulation I** Land-use restrictions
	Market III Reinforcement costs to producer	**Regulation II** Land-use designation
5	**Market I** Basic market scenario (Basic scenario)	-
6	**Policy Mix** Combination of **Regulation II** (Land-use designation) and **Market II** (Reference yield model)	

Table 1: Applied policy scenarios

Market-based instruments use the price systems to set incentives or obstacles to steer the behaviour of the participating agents to avoid negative externalities. In the context of environmental issues there are manifold examples, like pollution taxes, subsidies, permit schemes or emission trading. A typical example in the case of the energy transition process in Germany are the Feed-In tariffs (FITs) of the Renewable Energy Source Act (EEG), which e.g. guarantees a remuneration for the electricity production out of RES. Therefore, the FITs are defined as a subsidy. Regulation based policies focus on the restriction of certain actions via regulation or land-use planning. In the case of RES land-use restrictions with respect to spatial disabilities are familiar. Table 1 provides an overview of the applied policy scenarios which will be described in detail in the subsequent chapter 4.

Market-based policy scenarios

The guaranteed compensation for the RES electricity production is an investment incentive on a national scale to enable the expansion of RES capacity. In the model context we focus on Feed-In tariffs (FIT) as one of the major subsidy strategies that can be identified in the European context (Reiche and Bechberger 2004; Kitzing et al. 2012).

Accordingly, the *Market I* scenario incorporates basic attributes of FIT systems. Producers are compensated with a fix price p for their averagely produced electricity. Furthermore, they are not responsible for the existing grid system, which means they are free to choose a connection grid point and therefore do not have to pay reinforcement costs. Nevertheless, producers have are responsible for the connection of the RES plant to the existing grid infrastructure. Moreover, the *Market I* scenario serves as our basic scenario, which will be used in the following chapter as reference point for the effectiveness and efficiency of an introduced policy.

The *Market II* enhances the *Market I* scenario with a reference yield model (*Referenzertragsmodell*), which is part of the Renewable Energy Source Act to determine the compensation for the wind mill plants p depending on the average wind conditions at the plant location h. The mechanism has the objective to avoid windfall profits at locations with very good wind conditions and supports at the same time the wind power plant installations at landlocked locations with average wind conditions due to higher average payments per produced electricity unit.

In the third market-based policy scenario *Market III*, the producers are in charge of paying a certain part of the grid reinforcement costs C_{GE}. In order to create site-specific incentives to avoid unnecessary grid investments, these costs have to be differentiated from region to region depending on the grid properties and the distribution of electricity production capacities. In regions with a high demand and low a supply this cost component will be rather low and in the opposite case rather high, by the existence of certain grid bottlenecks.

All three market-based scenarios are setting incentives for the installation of additional RES capacity. Whereas the *Market I* scenario is based a on general price incentive, the *Market II* scenario is based on a site-specific incentive and the *Market III* consists of an additional site-specific obstacle depending on the existing grid infrastructure. Further details concerning the additional market based policies will be given in section 4.3.

Regulation-based policy scenarios

Typically, RES installations are restricted at specific ecological vulnerable sites or close to settlement areas, whereas particular suitable areas are designated for the RES construction if physical conditions are promising or if the spatial externalities are minimal at specific locations. In our model we distinguish between a land-use restriction and a land-use designation policy. A land-use restriction policy designates areas of special interests in which particular usages are unwanted. Such mechanisms are applied in the context of nature conservation or living environment protection. Land-use designation policies are typically used to steer the establishment of socially relevant infrastructure such as roads, railways or even RES. Section 4.2 focuses on a detailed description and examination of the particular regulation policies. Policies examples are given for the German case study together with existing model examples.

2.7 Enhancing the model plausibility

2.7.1 Overview

In order to enhance the model ability for theory development and application the basic parameters of the presented model approach have to be fitted to real world data (Thiele et al. 2014). This process is called model calibration. If no empirical data is available to determine the input parameters (Grimm et al. 2005; Railsback and Grimm 2012), reasonable criteria for the model outcomes have to be defined in order to rule out unrealistic behaviour.

For the presented model design we applied a mix of both techniques depending on the properties of the parameter and the availability of empirical information. But as we have to deal with a conceptual ABM design, the application of real world data sets is rather the exception. Generally the parameters can be distinguished in three parameter groups depending on the welfare variable impact within the basic market scenario. The first group includes all parameters which have a direct effect on the producer surplus. In the second group all parameters with an impact on the consumer surplus can be found. Within the third group all parameters with a direct effect on the spatial externalities are included. Table 2 provides an overview of all parameters together with the deduced parameter intervals after the application of the plausibility enhancing mechanism, which will be explained in more detail in section 2.7.2 and in section 2.7.3.

Producer surplus related parameters		
h_{max}	Maximum energetic yield potential	$5.2 - 7.8$
l_{PC}	Plant´s performance parameter	$1.08 - 1.62$
w_{PC}	Factor price of the respective plant type	$3.2 - 4.8$
w_{GC}	Factor price of the connection grid per distance	$0.048 - 0.072$
Consumer surplus related parameters		
Y_j	Electricity demand of the consumer centres	$40 - 60$
p_{max}	Consumers' willingness to pay	$1.2 - 1.8$
p	Price for electricity	1.0
m	Regional multiplier effect	$0.24 - 0.36$
w_{GE}	Reinforcement related factor price for the existing grid	$0.044 - 0.066$
External spatial cost parameters		
$x_{s_{max}}$	Maximum site-dependent external costs	$40 - 60$
α	Intensity parameter	$80 - 120$
β	Curvature parameter	$0.4 - 0.6$
δ	External spatial costs parameter	$0.04 - 0.06$
θ	Ratio between transport and production related external spatial costs parameter	$0.028 - 0.042$

Table 2: List of the applied basic parameter intervals

2.7.2 The harvest potential

So far the generation of the virtual landscape for the modelling process has been random within a determine interval. Only the neighbourhood values have been considered for the calculation of the energetic yield potential and the site-dependent external costs of a raster cell. But in terms of the energetic yield potential average wind condition data can be used to determine plausible distribution for a region, country or continent.

Therefore, we compared the distribution of the average wind speed data (1981 - 2001) from the German weather service (DWD 2014) measured in m/s at a height of 80 meters for different administrative subdivision for Germany, with the obtained energetic yield potential distribution of our virtual landscape. In order to guarantee the robustness of the wind distribution results, the municipality and district level have been compared without the detection of mayor differences concerning the shape of the distribution curve.

As the aim is to produce a similar distribution pattern in the model compared to real world data, the landscape generation algorithm was altered till the objected has been fulfilled. A tow step algorithm has been implemented, which first creates a cluster-like surface structure and then uses a proportion of the neighbourhood cells to smooth the transition among the cells. For the comparison of the model results with the DWD data a density function, which allows the illustration of value distribution, has been applied within R.

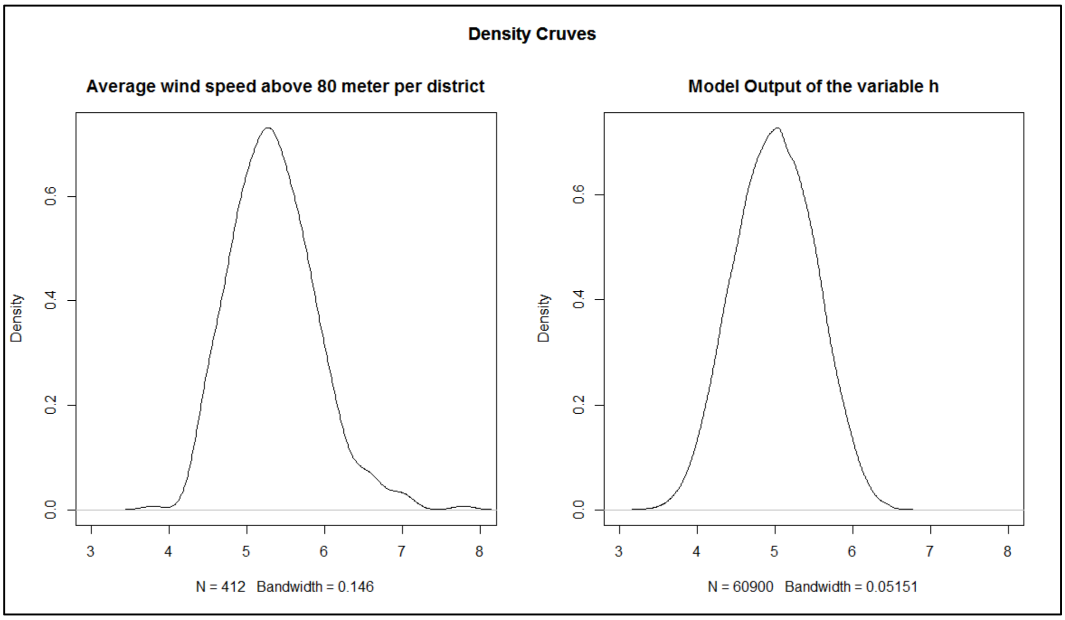


Figure 8: Distribution function of the real word data and the model output

Figure 8 shows the distribution functions of the average wind speed (at 80 meter heights) for German districts and the distribution of the parameter h after the generation of 100 virtual landscapes. Of course, the shapes of both curves are not completely identical but both share nearly the same mean and quantile values. Subsequently we can speak about an equal pattern despite the differences at the margins of both plots. A comparison to the average wind speed for German municipalities and the distribution of the parameter h after the generation of 100 virtual landscapes leads to similar model outcomes. Unfortunately we cannot apply a similar procedure for the site-dependent external cost as we do not have any information about the distribution of ecological costs. Therefore, we assumed a normal distribution within a cluster-based arrangement.

2.7.3 A pattern approach for the remaining parameter

After enhancing the plausibly of the virtual landscape also the remaining parameter have to be reasonable to guarantee plausible results. Accordingly, assumptions about the model outcomes have to be taken which reflect the real world situation. Afterwards parameter sets can be identified which support the taken assumptions.

In previous analysis with 1000 random virtual landscapes and a fixed parameter set, no significant differences have been obtained regarding the mean values of the welfare function, when using just one-tenth of the landscapes. Consequently, all plausible parameter combinations have been applied on 100 random generated landscapes to enhance the robustness of the model outcomes. Likewise we tested the influence of parameter variations concerning the producer surplus and the external costs within reasonable intervals to compensate the lack of information about a realistic scope of spatial externalities. If a certain generated virtual landscapes did not fulfilled all plausibility criteria with the presented parameter, the results have been neglected for the common evaluations. At the end a parameter set has been found which is consistent with all plausibilty criteria.

One objective of the ABM framework is to reflect spatial allocation mechanisms of wind mill producers. Therefore we can rely on literature information concerning the basic economic values. We know for example that the connection grid costs c_{GC} have to be in average less than 10% of the total producer costs c_n (WindGuard 2013) and the producer´s profit benchmark should be in average below 25% to reflect economic conditions. As we defined a plausibility criteria for the connection grid costs, the parameter w_{GC} has been fixed as a 10% ratio of the factor price of the respective plant type w_{PC}.

Additionally the total supply of all consumer centres with RES $Y^S \geq Y^D$ within the model ABM framework is only possible if the total welfare at the end of a complete model run stays beyond zero so that enough cells guarantee a positive profit $\pi_i \geq 0$. If this is not the case, no producer would have an incentive to invest in new RES capacities.

Spatial externalities are a conceptual idea which unit different spatial external cost categories. We assumed that both site- and distance-dependent external costs have an equal importance and cause therefore almost similar external costs. However, the spatial externalities form a production plant are by definition higher than the spatial externalities from a connection grid, which explains the relatively low ratio parameter θ that determines the transport and production related external spatial costs. The deduced plausible parameter set has been used to produce intervals with a two directional variation of 20% for each parameter. These intervals are important for further statistical analysis which will be carried out in the following chapter 3.

2.8 Summary and Conclusion

The presented agent-based model allows us to analyse the consequences on the spatial allocation of sustainable electricity infrastructures by testing a variety of policy scenarios. Therefore the model focuses on: (I) agent behaviour of producers and consumers, (II) overall cost functions that represents all types of costs (including especially spatial externalities), and (III) the constraint of ensuring a given electricity supply for a virtual landscape with renewable energy sources. For the complete model structure relevant entities, variables and scales have been defined (section 2.2.), the model procedure has been determined (section 2.3.) and different modules have been constructed (section 2.4.), which are in charge of different tasks, like spatially related calculations, the load flow model and the multi- criteria site assessment of the producers. A model run is completed if the total consumer electricity demand is supplied via RES.

The performance of different policy scenarios can be assessed under the aspect of the overall welfare of the virtual energy landscape and the distributional fairness among regions considering, besides the energetic potential of RES, also social and ecological impacts. Depending on applied market or regulation based policies, introduced in section 2.6, the site assessment procedure of the producer may change, which in turn can affect the resulting spatial allocation of the producers and therefore the evaluation criteria defined in section 2.5. For further analysis assumptions for the detection of a plausible basic parameter set have been made and the virtual landscape generation procedure has been altered to rule out unrealistic model behaviour and reflect literature based assumptions in section 2.7.

This model is based on an interdisciplinary discussion process linking economic theory to land-use decision modelling and load flow modelling in order to enhance the system understanding for spatial allocation mechanism of electricity infrastructure by taken relevant agent decisions (producer, consumer) into account.

Chapter 3

The model evaluation

3 *The model evaluation*

3.1 Overview

In order to test different policy designs we first have to understand the general interdependencies between the different model parts. Despite a deduced plausible parameter set we have to deal with a high grade of uncertainty within the conceptual model framework. Hence the virtual landscape will be generated randomly (following different generation steps) for every model run, the allocation of the producer plants often differ from one model run to another. Likewise the computed welfare components can change significantly between different model runs. Consequently, we have to run the model various times to produce reliable results due to the high sensitivity of the model outcomes.

Therefore, sensitivity analysis (SA) is applied to examine the influence of parameter variations on the model output (Saltelli et al. 2000; Railsback and Grimm 2012). It is an efficient tool to determine the model parameters' sensitivity to indicate the most important model parts. Beside the simple parameter characteristics also thresholds can be identified and analysed. Particularly for conceptual model designs this evaluation step is important, as this kind of model don´t rely on empirical data, with the consequence that their model inputs are for a certain degree uncertain (Thiele, Kurth et al. 2014).

We can distinguish between a linear and a global sensitivity analysis. For a linear analysis it is enough to examine the influence of one model parameter's variation on the model output. However, it is not possible to analyse any interaction effects between the different model parameters with a linear sensitivity analysis. For that reason all parameters have to be varied for a global sensitivity analysis. Consequently, we decided to use +/- 20% intervals of the deduced plausible parameter set which are shown in Table 2 within section 2.7 to produce samples for further examinations.

The model will be executed 1000 times to generate a sample with a reasonable size for the statistical analysis. For every model run a parameter set within the defined parameter intervals and a new virtual landscape will be generated, before the model procedure starts. Therefore, every model run consists of a different parameter vectors and different virtual landscapes. This kind of procedure is known as Monte Carlo Simulations.

3.2 The statistical evaluation model

To get insights about the mechanism of the presented model design it is not sufficient to only look at the descriptive statistical outcomes. Nevertheless we can obtain useful information from simple boxplots about the dispersion and data variability of the welfare equation components. For example it is possible to prove the consistency of the results with the taken plausibility assumptions.

Nevertheless we need more sophisticated methods to get an idea about the input output relationships of the ABM. Manifold approaches already exist for the simulation result analysis. A profound overview of the general techniques is given by Kleijnen (2007) whereas Saltelli et al. (2008) specifically focus on sensitivity analysis. In general it is important that the evaluation mechanism is strongly related to the design of the simulation experiment (in our case the ABM).

For the detailed examination of the produced sample we use a mix of multivariate linear regression models, based on the ordinary least square (OLS) method, and generalized additive models (GAM) (Hastie and Tibshirani 1986) to identify the effect of parameter variations on the model outcome. The OLS coefficients are used to interpret the directional effect of the parameters and the GAM model is used to determine the functional interdependence between a parameter and an evaluation criteria. In general the GAM models can be seen as extension of multiple linear models, due to the integration of a non-linear function for every explanatory variable, while maintaining the property of the general model’s additivity. Therefore, it allows smooth functions of covariates within the linear predictor. We use the R-package *mgcv* by Wood (2006) that contains of an implemented cross validation method to overcome overfitting problems which occur when a statistical model describes random error or noise instead of the underlying relations.

$$y_i = \beta_0 \sum_{j=1}^{k} f_j(x_{ij}) + \varepsilon_i \tag{21}$$

Above we see an example for a GAM, whereas β_0 represents the intercept, ε_i the error term per observation and k the number of used parameters. The function f_j is a smoothing function of the covariate x_j. The *mgcv* implementation of the GAM represents the smooth functions via penalized regression splines by adding a roughness penalty which controls how wiggly the function $f_j(x_{ij})$ is and how many degrees of freedom will be used. Therefore, a smoothing parameter will be calibrated via a leave-one out cross validation mechanism. The model design allows us to show nonlinear relations between the dependent and the explanatory variable. This can be useful to identify threshold effects and to rank the parameters concerning their model outcome importance. For our detailed analysis we will focus on the GAM's main effect outcomes. They show the variation of the dependent variable under the variation of one explanatory variable while holding the remaining explanatory parameters fixed.

3.3 The sensitivity analysis for the examination of the basic market scenario

3.3.1 Overview

The foundation for the first results is a produced sample with the outputs of 1000 completed model runs. We focus on the influence of varied parameter settings on the efficiency and fairness. Consequently, the overall welfare (W) of a virtual landscape after a completed model run (efficiency) and the regional differences within the catchment areas of the consumer centres ($Gini$) will be examined.

But before we start with the detailed analysis we take a look on the descriptive outcomes of the produced sample. Therefore, Figure 9 illustrates the boxplots of the welfare and concerning welfare components. Due to the plausibility criteria, no model run within the sample has a negative overall welfare W or producer surplus PS. But the consumer surplus CS is in some cases below zero because of the fact that the consumer centres have to pay the reinforcement costs of the grid infrastructure C_{GE} under the basic market scenario setting *Market I*. Furthermore, all model runs lead to a certain amount of spatial externalities X. The large distances between the vertically extending lines (called whiskers) indicate the high outcome variability between the ABM runs of the created sample. That is especially the case for the welfare $W$and the consumer surplus CS whereas the outcomes for the producer surplus PS and the externalities X seem to be more stabilized.

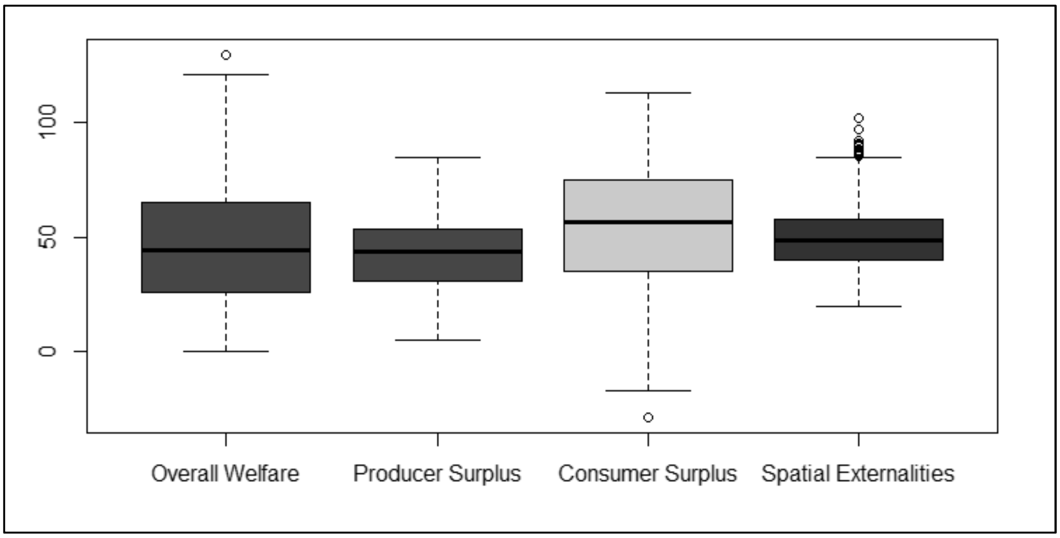


Figure 9: Boxplot of the basic market scenario overall welfare and crucial welfare components

3.3.2 Efficiency evaluation of the basic market scenario

Concerning the efficiency of the model all varied basic parameters have been included in a multiple linear regression model and in a GAM as explanatory variables vector to measure their importance on the overall welfare outcomes of the ABM as dependent variable. In Figure 10 the GAM's main effects of all parameters from Table 2 are illustrated. After having examined the adjusted R-square of the statistical model we see in Table 3 that 31.1% of the resulting deviance can be explained by the variation of the input parameters with the GAM and 28.4% by the multivariate linear regression model. Therefore, the major part of the variance is explained by other factors than the initial parameter setting. As the only the random virtual landscape generation step is not included in the statistical model, we can see that as a first indication of the importance of the virtual landscapes' design, which determines the resulting spatial allocation of the RES-producers.

The shapes of the main effect curves with their specific slopes reveal insights about the influence of a specific parameter on the welfare outcomes, which are at the same time consistent with the resulting significance levels of the parameters seen in Table 3. Accordingly, the importance of the parameters' variations of h_{max} , l , Y_D , w_{PC} , p_{max}, m , $x_{s_{max}}$, α and δ on the overall welfare is high in comparison to the other non-significant parameter.

The importance of the wind condition parameter h_{max} is consistent with the real world data about wind power capacities' expansions rates, which often take place at sites with wind conditions above average, which can be found in general close to the coast lines or at mountain plateaus. Examination of wind power development criteria for Sweden and the United States (Ek et al. 2013; Hitaj 2013) showed similar results concerning the aspect of wind conditions and onshore wind power deployment. Consequently in both examinations the criteria wind conditions has been highly significant despite the use of different statistical models in both countries. That is not surprising due to the fact that the cumulative remuneration per support scheme strongly correlates positively with the measured wind condition of a location.

In terms of power plant efficiency l and prices w_{PC}, the main effect results of the model outcomes underline the plausibility of the taken assumptions during the model construction process. According to the results we see that higher plant efficiency leads to an increase of welfare. One reason is the reduction of necessary plants for the supply of the electricity demand due to an increase of the location based efficiency. With less plants needed the spatial externalities, due to negative social and ecological impacts, can be reduced for the virtual landscape. The opposite effect can be observed while examining the influence of the power plant prices, which means that a decrease of the power plant prices lead to an increase of the welfare. This can be mainly explained with the higher generated producer profit ranges, which consequently lead to an increase of the producer surplus within the model framework. Please note that we assume the virtual landscape to be embedded within a higher market mechanism. Accordingly, the negative aspect of an extensive promotion of the RES does not have any influence on the overall welfare outcome of the virtual landscape.

The effects of the overall demand of the consumer centres Y_D are not as clear as in the previous case. In the multiple linear regression model we see a significant effect for the parameter whereas the same is not the case for the GAM. The parameter Y_D is connected to the energy efficiency realm. In general the society can benefit from an increase in energy efficiency. Blesl et al. (2007) for example found out that a reduction of the electricity demand in Germany would have positive effect on the decrease of CO^2 emissions, which can be defined as negative external effect of the conventional energy production process. Therefore negative externalities of the electricity production process can be reduced when the electricity demand decreases. Consequently, less negative spatial externalities, because of the installation of RES, arise when the electricity demand decreases. But this effect is opposed by the rise of the consumer surplus and the regional multiply effect of RES.

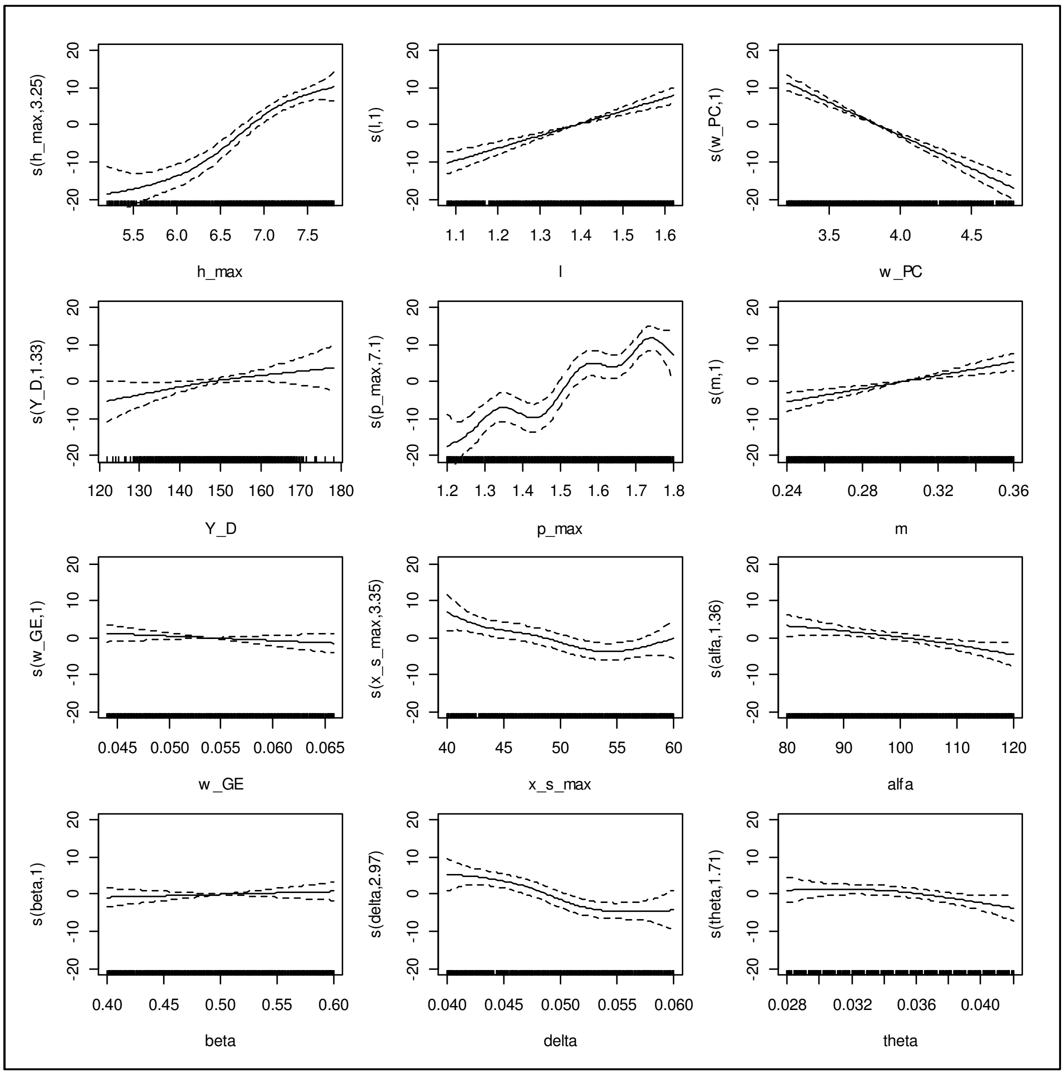


Figure 10: Model parameter main effects of the GAM (Efficiency)

An increase of the significant parameters p_{max} and m has a positive impact on the consumer surplus and therefore on the overall welfare. The results concerning the relationship between the maximal willingness to pay and the consumer surplus are consistent with the general economy theory, whereas a higher difference between the paid price and the willingness to pay lead to a higher benefit for the consumer. As the parameter m measures the multiplier effect due to the regional electricity production out of RES within a region, we have to take a closer look at the added value literature for RES.

Results of the multiple linear regression model

Parametric coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	
$Intercept$	-63.01724	23.88291	-2.639	0.008456	**
h_{max}	13.35540	1.11542	11.973	< 2e-16	***
l_{PC}	33.41600	4.74123	7.048	3.41e-12	***
w_{PC}	-17.45629	1.62797	-10.723	< 2e-16	***
Y_j	0.16493	0.07339	2.247	0.024839	*
p_{max}	48.55970	4.30857	11.270	< 2e-16	***
m	89.11000	20.55729	4.335	1.61e-05	***
w_{GE}	-124.88689	114.12960	-1.094	0.274110	
$x_{s_{max}}$	-0.41787	0.12420	-3.365	0.000796	***
α	-0.19487	0.06197	-3.145	0.001712	**
β	5.22921	12.28198	0.426	0.670373	
δ	-656.14690	125.77823	-5.217	2.22e-07	***
θ	-336.96053	178.24368	-1.890	0.058991	.

R-sq.(adj) = 0.275 Deviance explained = 28.4%

GCV = 511.66 Scale est. = 505.01 n = 1000

Results of the generalized additive model

Parametric coefficients:	Estimate	Std. Error	t-value	Pr(>|t|)	
$Intercept$	463.737	0.7022	66.04	<2e-16	***

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value	
$s(h_{max})$	3.254	4.038	36.547	< 2e-16	***
$s(l_{PC})$	1.000	1.000	50.622	2.10e-12	***
$s(w_{PC})$	1.000	1.000	118.562	< 2e-16	***
$s(Y_j)$	1.329	1.592	2.519	0.09109	.
$s(p_{max})$	7.096	8.142	17.383	< 2e-16	***
$s(m)$	1.000	1.000	18.915	1.51e-05	***
$s(w_{GE})$	1.000	1.000	1.152	0.28332	
$s(x_{s_{max}})$	3.346	4.147	4.396	0.00142	**
$s(\alpha)$	1.358	1.631	5.256	0.01009	*
$s(\beta)$	1.000	1.000	0.433	0.51080	
$s(\delta)$	2.970	3.694	8.196	4.97e-06	***
$s(\theta)$	1.711	2.126	2.555	0.07458	.

R-sq.(adj) = 0.292 Deviance explained = 31.1%

GCV = 506.76 Scale est. = 493.05 n = 1000

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 3: Efficiency results of the applied regressions models

Hirschl, Aretz et al. (2011) and Aretz et al. (2013) examined the effect for Germany with the help of a quantitative model. Regarding to the model the added value from RES mainly depends on three things: the revenue of the participation companies, the income of the participation employees and the commercial taxes. The parameter m illustrates this effect in a very simple manner. Consequently, the increase of m can be defined as an increase of one of the dependent factors. Therefore, the result of the model outcome concerning the relationship between m and the overall welfare is again consistent with real world observations.

The impact of the spatial externalities is linked to various model parameters. Not all of them have a significant impact on the welfare outcome. However, the parameters $x_{s_{max}}$, α and δ, which mainly determine the allocation of the and amount of the spatial externalities within the virtual landscape, are illustrated with a negative slop. Unfortunately it is not possible to compare the results with empirical findings due to the theoretical reasoning behind the term spatial externalities, which includes besides social also ecological impacts. Nevertheless the model results are consistent with the taken assumptions for the ABM. Accordingly, an increase of these kinds of parameters has a negative effect on the overall welfare, due to the rise of site dependent and distance dependent externalities.

The grid reinforcement parameter w_{GE} is not significant. Consequently, the virtual landscape configuration has a higher impact on the resulting reinforcement costs in comparison to the factor price w_{GE}.

3.3.3 Fairness evaluation of the basic market scenario

As defined in section 2.6 the fairness refers to the distribution of the regional net utility per capita among the consumer centres. To make the several model runs comparable we use a normed and adapted *Gini* coefficient to measure the fairness. But before we start with the analysis of the explanatory variables importance on the *Gini* coefficient, we have a general look at the distribution of the regional net utility per demand and the influence of the landscape parameter within the catchment area of the consumer centres.

Figure 11 shows two kinds of plots for every consumer centre, which are named as cities. The upper three plots illustrate the distribution of the regional net utility per capita csx_j among the 1000 model runs via a boxplot. Despite the different landscape properties between the consumer centres in one model run, all three boxplots show similar ranges and mean values. Consequently, we do not have to deal with a systematic bias between the three consumer centres.

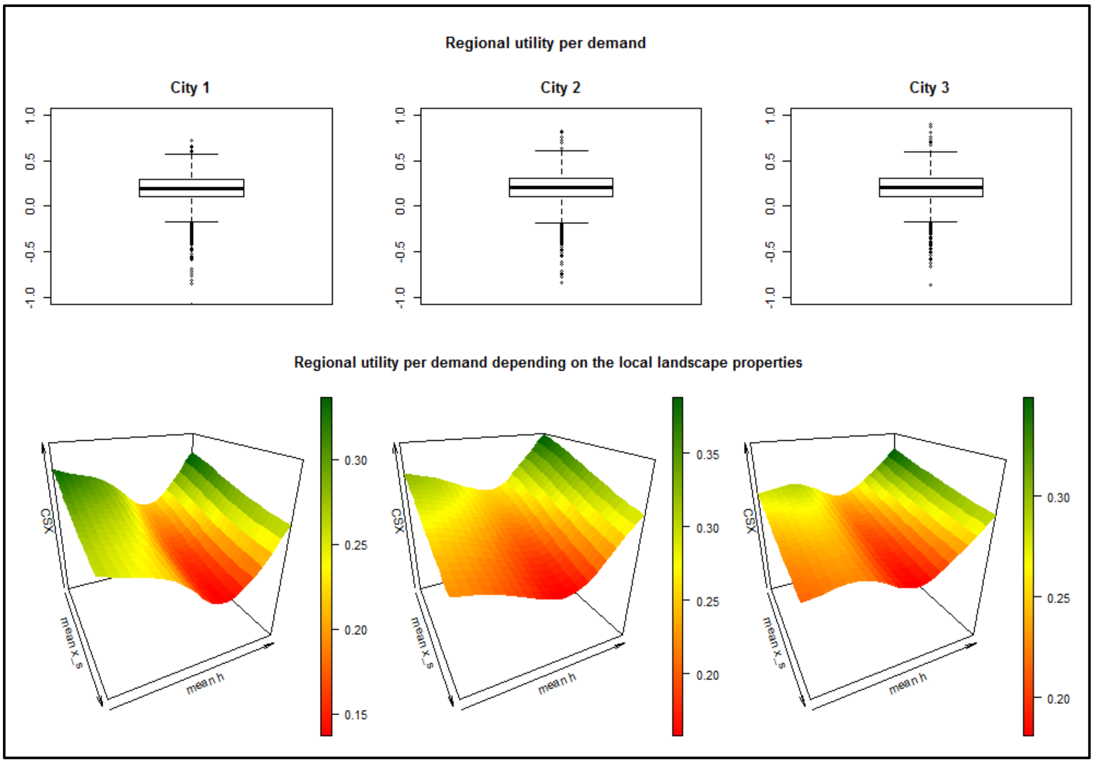


Figure 11: The regional net utility distribution of the consumer centres together with the landscape parameter impacts on the regional net utility of the consumer centres

The corresponding three 3-D plots visualize the regional net utility per capita on the z-axes, together with the virtual landscape related mean values for the catchment areas of the consumer centres, with the mean wind potential $mean\ h$ on the x-axes, and the mean site-dependent external costs $mean\ x_s$ on the y-axes. Similar to the other parameters we applied a +/-20% interval for the plot generation. Due to the applied GAM, whereas $mean\ h$ and $mean\ x_s$ have been the explanatory variable and csx_j the dependent variable, the resulting prediction functions of the GAMs are quite irregular in terms of the variable $mean\ h$.

Three different general observations can be obtained from the 3D-plots. First, it exists a realm within all 3D-plots for all consumer centres, where the regional net utility per demand is significantly lower than in the rest of the plot. The reason for that observation is the combination of high site-dependent external costs and average wind conditions within the consumer centre’s catchment area. Consequently, the RES installations generate low profits and therefore lead to low regional benefits, but have big negative ecological consequences for the region on the other side. Second, if the wind conditions are clearly above average the consumer centre seems to benefit despite spatial externalities’, hence the positive regional effects of the new installations surpass the negative ecological impact for this kind of landscape configuration. Likewise to the previous combination a catchment area with low site-dependent external costs and wind conditions below average also has positive implications for the affected consumer centre. As no installations will be realized, the consumer centre benefits from the transition process without being confronted with any spatial externalities.

The next analysis deals with the importance of the presented basic model parameter in Table 2 of section 2.7 on the *Gini* coefficient of a completed model run. Like in the efficiency examination we applied a multivariate linear regression model together with GAM. The results of both regression models are shown in Table 4 and the main effects of the GAM are illustrated in Figure 12. Both regression models produce consistent results. Accordingly, the significance of parameters does not change between the two statistical models. As the fairness increases with a decrease of the *Gini* coefficient, the coefficient has to be interpreted in a reversed manner. Again both models can only describe around 30% of the observed deviance of the dependent variables. That indicates the importance of not implemented independences outside the statistical scope.

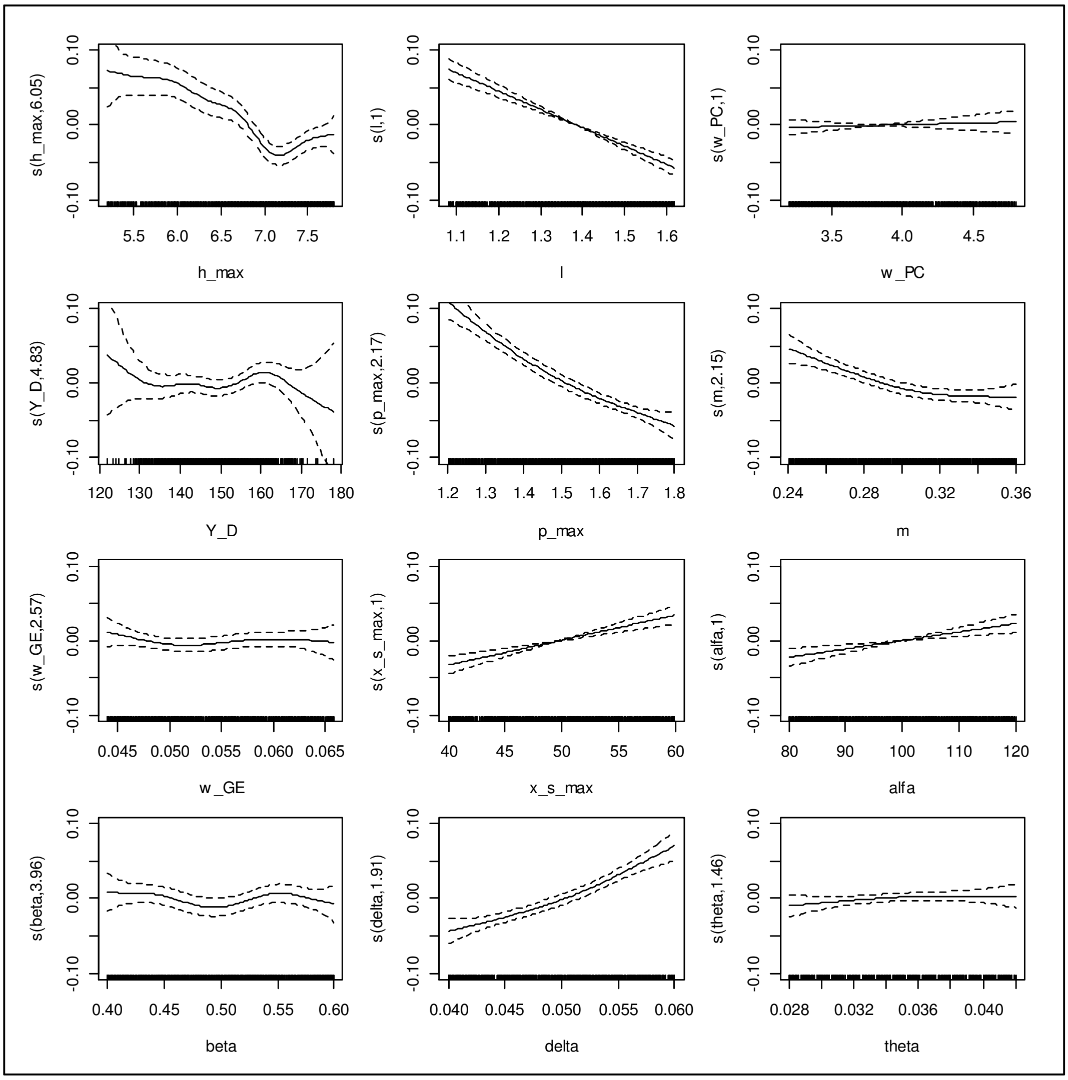


Figure 12: Model parameter main effects of the GAM (Fairness)

A higher plant efficiency l and good wind conditions h_{max} lead to a lower *Gini* coefficient and therefore to a higher general fairness. That can be explained with a general decrease of the negative spatial externalities, due to a smaller amount of necessary plants due to a location based efficiency increase. Accordingly, the negative externality impact on the regional net utility of the consumer centres decreases, as well.

Results of the multiple linear regression model (OLS)

Parametric coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
$Intercept$	0.8254872	0.1171332	7.047	3.42e-12	***
h_{max}	-0.0462844	0.0054706	-8.461	< 2e-16	***
l_{PC}	-0.2524772	0.0232533	-10.858	< 2e-16	***
w_{PC}	0.0024327	0.0079844	0.305	0.760669	
Y_j	0.0002105	0.0003599	0.585	0.558730	
p_{max}	-0.2630455	0.0211313	-12.448	< 2e-16	***
m	-0.5199886	0.1008228	-5.157	3.02e-07	***
w_{GE}	-0.2237179	0.5597463	-0.400	0.689481	
$x_{s_{max}}$	0.0030992	0.0006091	5.088	4.33e-07	***
α	0.0010877	0.0003039	3.579	0.000362	***
β	-0.0306015	0.0602367	-0.508	0.611552	
δ	5.5031190	0.6168767	8.921	< 2e-16	***
θ	1.0123772	0.8741924	1.158	0.247115	

R-sq.(adj) = 0.288 Deviance explained = 29.6%

GCV = 0.012308 Scale est. = 0.012148 n = 1000

Results of the generalized additive model (GAM)

Parametric coefficients:

	Estimate	Std. Error	t-value	Pr(>|t|)	
$Intercept$	0.176026	0.003403	51.73	<2e-16	***

Approximate significance of smooth terms:

	edf	Ref.df	F	p-value	
$s(h_{max})$	5.890	7.041	13.950	< 2e-16	***
$s(l_{PC})$	1.000	1.000	112.837	< 2e-16	***
$s(w_{PC})$	1.000	1.000	0.365	0.545613	
$s(Y_j)$	4.440	5.542	0.786	0.572018	
$s(p_{max})$	2.076	2.598	62.747	< 2e-16	***
$s(m)$	2.168	2.697	12.923	2.05e-07	***
$s(w_{GE})$	2.517	3.135	0.831	0.479010	
$s(x_{s_{max}})$	1.000	1.000	30.547	4.15e-08	***
$s(\alpha)$	1.000	1.000	14.281	0.000167	***
$s(\beta)$	4.113	5.061	1.033	0.396700	
$s(\delta)$	1.872	2.342	37.000	< 2e-16	***
$s(\theta)$	1.215	1.397	1.260	0.260502	

R-sq.(adj) = 0.321 Deviance explained = 34%

GCV = 0.01193 Scale est. = 0.01158 n = 1000

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 4: Fairness results of the applied regressions models

All consumer surplus relevant parameters, like p_{max} and m, have a strong impact on the decrease of the *Gini* coefficient, which can be explained with higher consumer related benefits for the virtual landscape, if the mentioned parameter increase. The parameters which have a negative fairness impact are related to the negative ecological and societal aspect of RES. Therefore, the spatial externality related parameters $x_{s_{max}}$, α and δ leads to an increase of the Gini coefficient. Again site- and distance-dependent parameters are affected, whereas the strongest slope can be observed for δ which is responsible for the importance of both spatial externalities in general. The negative impact of spatial externalities on the consumer centre´s regional net utility finally leads to the fairness decrease.

Like in the previous efficiency analysis we do not observe a significant relationship between the grid reinforcement parameter w_{GE} and the fairness outcome. Accordingly, one can argue that the landscape configuration (the cell specific distribution of landscape values) is of higher importance.

3.4 Summary and Conclusion

Within this chapter 3 we introduced evaluation strategies to get insights on the model mechanism of the ABM. Therefore, we used a sensitivity analysis variation where all model parameters can be changed randomly within a defined interval. Afterwards a sample of 1000 Monte Carlo Simulations has been statistically evaluated with the help of a multivariate regression function based on OLS and more advanced GAM due to the implementation of parameter specific smoothing functions.

To gain first insight about the ABMs basic market scenario *Market I* the defined evaluation criteria (efficiency and fairness) have been used as dependent variables together with the basic model parameters as explanatory variables. The encountered parameter variations effects on the efficiency and fairness are consistent with real world observations and initial expectations, so that the model can be seen as a reliable tool for further policy analysis. Furthermore, the evaluation strategy can be seen as an efficient way to identify the inner mechanism of the ABM framework.

Chapter 4

The efficiency and fairness impact of policies

4 The efficiency and fairness impact of policies

4.1 Overview

After the definition of an evaluation scheme in chapter 3, including the evaluation of the basic *Market I* scenario, all additional policy scenarios, which have been laid out in section 2.6, will be further analysed within this chapter 4. Therefore, the different policy scenarios will be described in more detail. Furthermore, additional model extensions will be carried out in order to implement the different policy designs.

In a first step all regulation-based policies, which differ between land-use restriction (*Regulation I*) and land-use designation (*Regulation II*) policies, will be examined in section 4.2. An overview of general regulation based land-use policies will be provided in section 4.2.1 before the model implementation strategy will be laid out in section 4.2.2 and the results will be discussed in section 4.2.3.

Then additional market-based variations in form of a reference yield model (*Market II*) and a re-allocation of the grid reinforcement costs to the producer (*Market II*) will be introduced in section 4.3. The section starts with the market-based scenario *Market II* under 4.3.1 before coming to the market-based scenario *Market III* under 4.3.2. In both cases an overview on the scientific and practical context will be given and an overview about the model strategy will be provided before the scenarios will be evaluated concerning their impact on the model's efficiency and fairness.

4.2 Regulation-based land-use policies

4.2.1 A general overview about regulation-based land-use policies

Multiple options for regulatory interventions on various scales to steer land use decisions of RES producers can be identified. Generally they have the aim of nature conservation or social environment protection to avoid a chaotic proliferation of RES plants. In other words, RES installations can be excluded from specific ecological vulnerable sites or in the direct neighbourhood of settlement areas (see section 1.2). Some countries have even developed procedures for the designation of particular suitable areas for RES installations. Planning and sitting methods differ among countries depending, besides other factors, on the planning system, the system of financial support, the landscape protection organization and local ownership patterns (Toke et al. 2008).

The increasing implementation of RES makes it necessary to adapt existing planning mechanisms due to the increasing spatial pressure (Bosch 2011) and the resulting demand for more planning participation. A continuous adaption process is important in order to guarantee public acceptance due to the avoidance of top down planning and a lack of available space for RES because of negative planning. Zaspel (2014) discusses for example regional spatial quotas and designation of priority areas as reasonable tools to steer the proliferation of RES within Germany.

To address both nature conservation and social environment protection goals, various GIS-based approaches have been developed to identify suitable locations for the installation of onshore wind power plants for certain regions. Examples can be found for Northern California (Rodman and Meentemeyer 2006), the UK (Baban and Parry 2001) or other European countries. Cowell (2010) examines e.g. how location are defined as *acceptable locations* for wind farms in a Welsh case study. Likewise, conservation areas and settlements’ distances are taken into account via a scoring scheme. Eichhorn and Drechsler (2010) extended these frameworks with an integration of bird risk maps to provide a trade-off between energy production and bird mortality for a particular region in Saxony, Germany. However, all these models are static examinations of certain regions under a current policy regime with some thematic extensions.

We want to compare different kinds of regulation-based land-use policies with the help of the implemented model design. Therefore, we distinguish between a restriction policy and a designation policy, which focus on different kinds of criteria. Concerning the land-use restriction policy we apply a distance- and site-dependent approach. For the distance-dependent land-use restriction policy all cells within a certain distance to the consumer centre will be restricted for the installation of wind power plants.

In the case of Germany the Federal Pollution Control Act (BImSchG 2014) determines the minimal distance of a wind mill to settlements on a national scale. For the site-dependent land use restriction the site-specific costs are relevant. Consequently, RES installations are not allowed on cells with a high ecological sensibility rates and therefore with high site-dependent external costs. This type of regulation is comparable to the designation of nature conservancy areas. The German Federal Act for the Protection of Nature (BNatSchG 2013) defines for example different kinds of area categories to determine allowed usages and to ensure the purpose of nature conservation and sustainable landscape management.

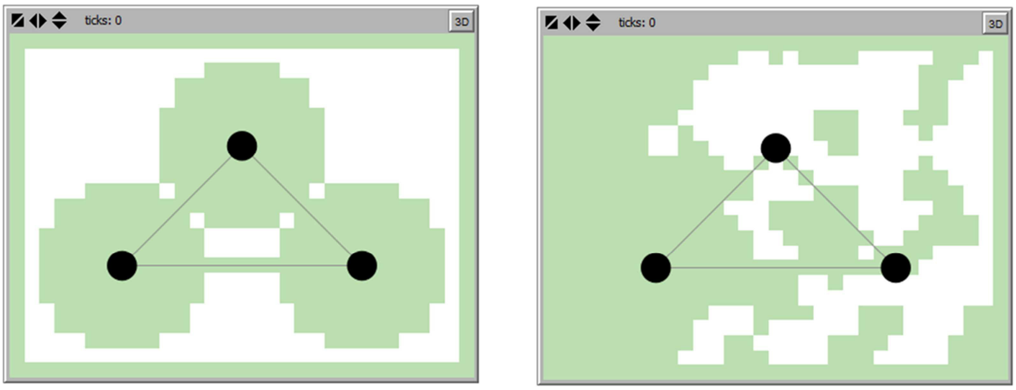
In comparison to the land-use restriction policy land-use designation policy tries to identify specific areas for particular infrastructures of common interest, which can be e.g. roads, railways, electricity grids, power plants, etc. We distinguish between a maximized output orientation and a minimized external spatial cost orientation which in the following will be called harvest-dependent land-use designation and external cost dependent land-use designation. Now the consumer centres have to designate a certain percentage of their catchment area following the two different land-use designation approaches. In the case of Germany the Federal Regional Planning Act (Raumordnungsgesetz 2008) contains all details concerning the different area types which regions can designate to provide areas for the installations of RES. Thereby regions can follow different strategies concerning their area designation policies. Ohl and Eichhorn (2010) for example illustrate the trade-off between fulfilling the support criteria regarding the local wind conditions and the social and ecological impact.

4.2.2 Model Implementation and extension

Concerning the land-use restriction policy we distinguish between a site- and distance-dependent land-use restriction with the land-use restriction parameters lur_d and lur_s representing the restricted area share in % within the interval of [0,100] by taking the total available area of the virtual landscape into account. Depending on the defined value of lur_d all cells within a certain distance to the consumer centre will be restricted, whereas in the case of the parameter lur_s the cells with the highest site-dependent external costs will be restricted first. For the land-use designation policy we use the parameter lud_h for harvest-dependent land-use designation and lud_x for external costs dependent land-use designation. For reason of comparability of all regulation policies we always measure the restricted area. Therefore, both parameters measure the restricted area per region in % within an interval of [0,100].

The installation of connection grids is only restricted at especially vulnerable sites with costs above the mean value of x_S , as installations of connection grids from the RES plant to the existing grid structure have to be guaranteed. However, the connection grid costs double if a grid passes a site-dependent restricted cell, as the connection grid cost implementation effort increases in such circumstances.

Distance-dependent land-use restriction Site-dependent land-use restriction



Harvest-dependent land-use designation External cost dependent land-use designation

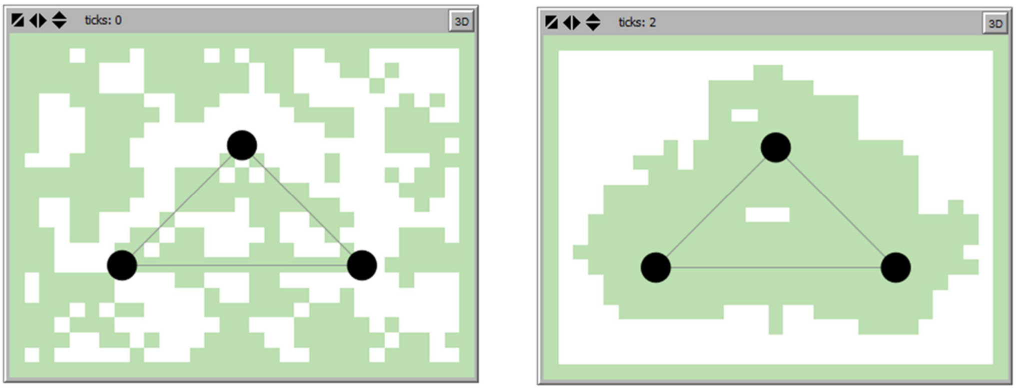


Figure 13: NetLogo screenshots of four virtual landscapes with a applied specific land-use policy, whereas all green cells are restricted for the installation of wind mills.

In Figure 13 four virtual landscapes with all defined land-use policies are illustrated. In all cases 50% of the available cells of the virtual landscape are restricted to the installation of wind power plants, therefore, the parameters lur_d, lur_s, lud_h and lud_x share a value of 50. For all cases the white areas are not restricted or designated for the installations of wind power plants. Note that the fringes of all landscapes are always restricted for any installation of wind power plants due to boundary effects which occur during the virtual landscape generation procedure. One major difference between the land-use restriction and the land-use designation policy is the distribution of the restricted area. In the case of the designation policy all regions share the same amount of restricted cells, whereas site-dependent land-use restrictions can be unequally distributed among the catchment areas of the consumer centres.

4.2.3 The sensitivity analysis for the examination of regulation-based land-use policies

In the chapter 3 we examined the importance of parameter variations on the efficiency and fairness outcomes of the basic market scenario. Now we are going to compare different regulation-based policies with each other to test their effectiveness in general. Therefore, we focus on the change of the efficiency and fairness criteria among the policy scenarios. In the following we define that procedure as a policy experiment.

Consequently, we run the model with the similar basic parameters, which are shown in Table 2, and the similar generated virtual landscape with various policy scenarios. Then we can compare the different policy scenarios with each other based on the similar starting conditions. Again the basic parameter set will be generated randomly on the basis of the +/- 20% interval before the virtual landscape will be generated, as already mentioned in section 2.7. Thereafter all policy scenarios will be applied. This procedure will be repeated 1000 times, so that we again have a sample which can be analysed with the help of the introduced statistical models in chapter 3. Note that the policy parameters differ within the interval of [0,100] among the 1000 model runs which allows us to calculate the effect of increasing land-use restrictions or land-use designation on the model’s efficiency and fairness outcomes.

As we now focus on the illustration of the policy effect we only apply GAM, which results from the application of both statistical models in chapter 3, where the OLS and the GAM did not show mayor differences concerning the p-value of both regression models. To measure the policy efficiency we calculate welfare’s absolute rate of change from the market scenario to the policy scenario within the same basic parameter and landscape setting. Therefore, the welfare rate of change is our dependent variable. The application of relative terms is not possible due to the generation of extreme values.

$$y_i = \Delta W = W_{policy} - W_{Market\ I} \tag{22}$$

For the policy influence measurement regarding the fairness outcomes, the normed *Gini* coefficient of the resulting regional net utility per capita csx_j is used. Again the absolute rate of change has been applied, because of facing the risk of extreme values.

$$y_i = \Delta Gini = Gini_{policy} - Gini_{Market\ I} \tag{23}$$

Efficiency

As a first step we proved the significance of the policy parameters. Therefore, ΔW has served as dependent variable and the policy parameter, together with the basic model parameter (seen in Table 2), have been used as explanatory variable. A flexible GAM has been carried out to calculate the p-value of the four policies. Table 5 illustrates the obtained p-values regarding the smooth terms of the prediction model.

Only the distance- and site-dependent land-use restrictions have a significant impact (assuming a significant level of $p - value < 0.05$) on ΔW and consequently on the model efficiency. Furthermore, we observe a high significance of the parameter p_{max} for all policy scenarios. As p_{max} does not have any spatial influence, we can assume that the parameter does not have an impact on the general impact of a policy.

In the case of the distance-dependent land-use restriction we see that also the parameter l, which measures the harvest performance of an energy plant, and the parameter θ, which determines the intensity differences between external spatial costs due to production and the transportation infrastructure, matter. After the application of a simple OLS with the same parameter combination and a look at the main effects of the GAM we see that the model coefficient of the parameter l is positive, whereas the coefficient of θ is negative. Consequently, the effectiveness of a distance-dependent land-use restriction increases if the number of production plants decreases, which leads vice versa to less externalities.

Approximate significance of smooth terms:

	Distance		**Site**		**Harvest**		**Spatial Ex.**	
	p-value		p-value		p-value		p-value	
s(*Policy-parameter*)	< 2e-16	***	< 2e-16	***	0.0934	.	0.62173	
$s(h_{max})$	0.3854		7.98e-05	***	0.1688		0.83583	
$s(l_{PC})$	0.0267	*	0.00464	**	0.3109		0.56508	
$s(w_{PC})$	0.8281		0.00422	**	0.4529		0.18901	
$s(Y_j)$	0.9850		0.01924	*	0.8324		0.40081	
$s(p_{max})$	5.82e-06	***	0.00110	**	0.0122	*	0.00226	**
$s(m)$	0.1217		0.73564		0.2495		0.19438	
$s(w_{GE})$	0.4273		0.04656	*	0.5505		0.63166	
$s(x_{s_{max}})$	0.3100		0.84844		0.4007		0.82436	
$s(\alpha)$	0.8348		0.18582		0.0572	.	0.57492	
$s(\beta)$	0.1908		0.43578		0.6588		0.09410	.
$s(\delta)$	0.6085		0.62300		0.0409	*	0.43369	
$s(\theta)$	0.0282	*	0.29702		0.3587		0.98290	

\---

Signif. : 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1

R-sq.(adj)	0.199	0.149	0.0224	0.015

Table 5: P-Value of the regulation-based policy parameter

Six parameters (besides the policy parameter) have an effect on the overall welfare development regarding the GAM for site-dependent land-use restrictions: The wind conditions via the parameter h_{max}, the overall demand Y_D, and the performance parameter l determine the number of plants needed to supply the demand of the virtual landscape. As fewer plants produce less spatial externalities, the coefficients of an OLS of h_{max} and l are positive, whereas the coefficient of the demand parameter Y_D is negative. The significance of the reinforcement costs parameter w_{GE} indicates a high sensibility concerning the reinforcement costs of the grid infrastructure.

For the visualisation of the consequence of rising restrictions or designation levels we use the smoothing spline function within R (Hastie and Tibshirani 1986). The curves are calibrated via a leave-one out cross calibrations mechanism. Furthermore, the corresponding confidences bands of the prediction function are added via dotted lines. On the x-axes the restricted area in % in the case of the land-use restriction policies, or the designated area in % in the case of the land-use designation policies is shown, whereas the welfare development is illustrated on the y-axes. Every light grey dot is the result of one completed model run.

The results in Figure 14 suggest that the distance-dependent land-use restrictions, till a restriction level below 30%, and the external costs dependent land-use designation policy generally have a positive effect on the welfare development. Harvest-dependent land use designations do not affect the welfare in general and site-dependent land-use restrictions have in general a negative impact on the efficiency.

Despite the application of a flexible prediction model the explained deviance of the dependent variable ΔW and thereby the adjusted R² of all policy scenarios are relatively low. Consequently, other criteria, besides the considered parameters, seem to have an influence on the effectiveness of the policies.

As the exclusively negative slope of the site-dependent land-use restrictions are not intuitive we will analyse this specific case more in detail in order to understand the trade-off between the decrease of negative spatial externalities and the decrease of the producer surplus. However, that gives us the chance to consider the criteria of the initial distribution of the wind power plants in the basic market scenario, which have been neglected in the GAM. Therefore, the effect of the site-dependent land-use restriction parameters on the development of the producer surplus, the consumer surplus and the spatial externalities will be analysed with a further smoothing spline function.

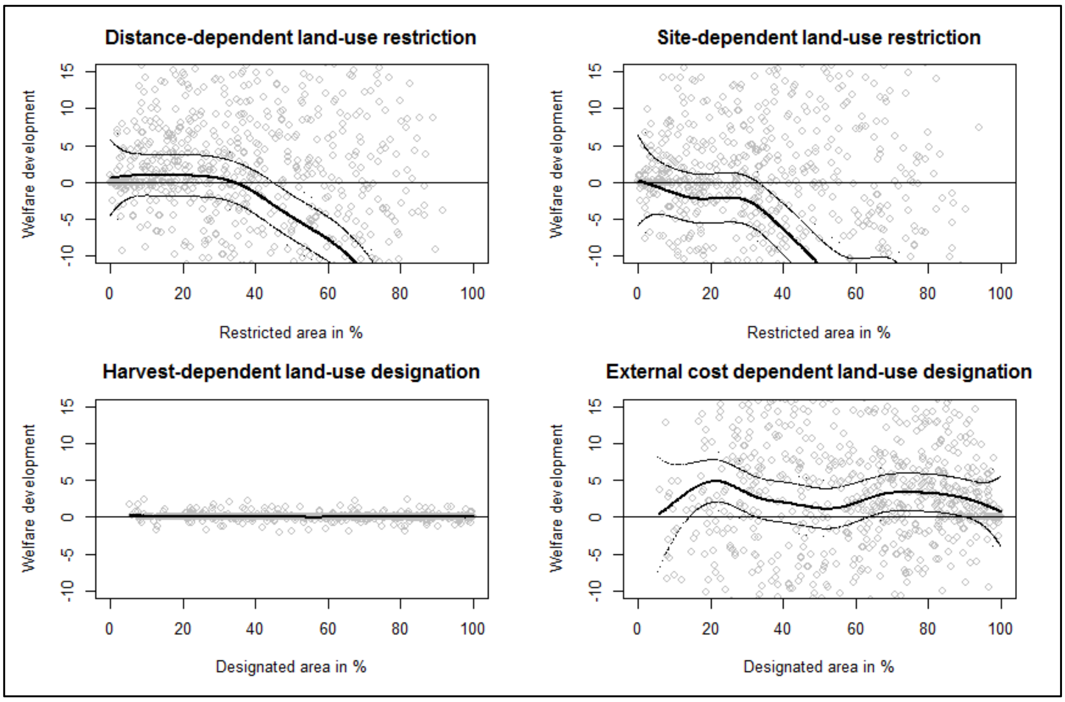


Figure 14: Smoothing splines concerning the influence of regulation-based policy parameters on the efficiency

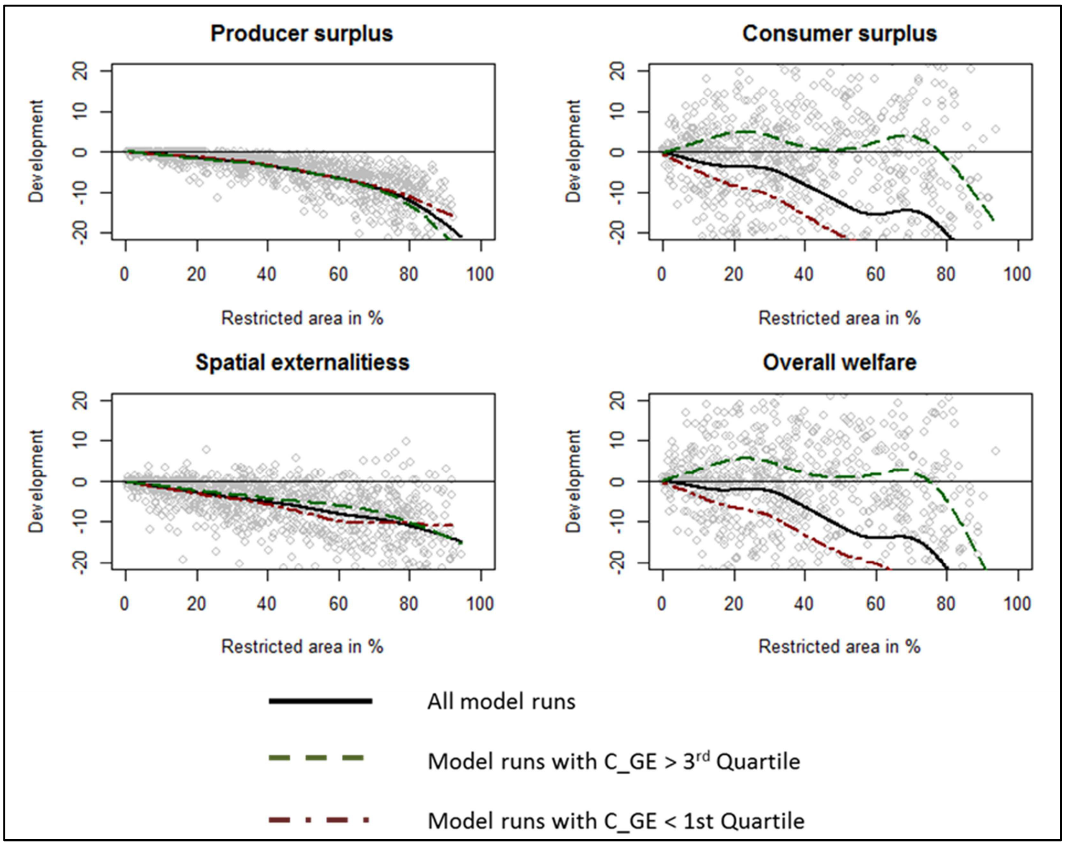


Figure 15: Smoothing splines concerning the influence of the site-dependent land-use restriction parameters on the producer surplus, consumer surplus, spatial externalities and overall welfare in dependence on the initial reinforcement costs

To include the initial spatial distribution of the wind power plants we focus on the resulting grid reinforcement costs C_{GE} of the basic market scenario *Market I*. If the production capacity is evenly distributed, C_{GE} is close to zero, but if the complete production capacity is concentrated in one part of the virtual landscape, the grid capacity has to be reinforced in order to guarantee the distribution of the electricity to all three consumer centres, which vice versa leads to an increase of C_{GE}.

Figure 15 illustrates smoothing splines of the site-dependent land-use restriction parameter with regard to the development of the producer surplus ΔPS, the consumer surplus ΔCS, the spatial externalities ΔX and the overall welfare ΔW after the application of a certain restriction level. Every plot consists of three different smoothing splines. The complete sample has been used for the calculation of the black line. For the green dashed line only the model runs with initial basic market scenario reinforcement costs C_{GE} above the third quartile of the overall sample have been included. Therefore, only the model runs with a concentrated wind power capacity distribution during the basic market scenario have been taken into account for that sample. The red dashed dotted line consists of all model runs with initial basic market scenario reinforcement costs C_{GE} below the first quartile of all model runs, which means that these model runs show a more evenly wind power plant capacity distribution after the application of the basic market scenario.

We see that the spatial externalities decrease linear with an increase of the area restriction level, whereas the producer surplus decreases in an exponential manner. Without considering the consumer surplus, high area restriction levels would always lead to a welfare decrease. But also a high dependence concerning the consumer surplus is visible. As the reinforcement costs are the spatially dependent part of the consumer surplus we can attribute the differences to an change of C_{GE}. Therefore, the results reveal a suggested dependence of the initial wind power plant distribution on the policy efficiency impact. Site-dependent land-use restriction policies are more effective if wind power plants are highly concentrated by absence of any land-use restriction policy. The four different plots of Figure 16 show that a similar effect also occurs for the other regulation-based land-use policies except for the harvest-dependent land-use designation, which seems to have no effect at all.

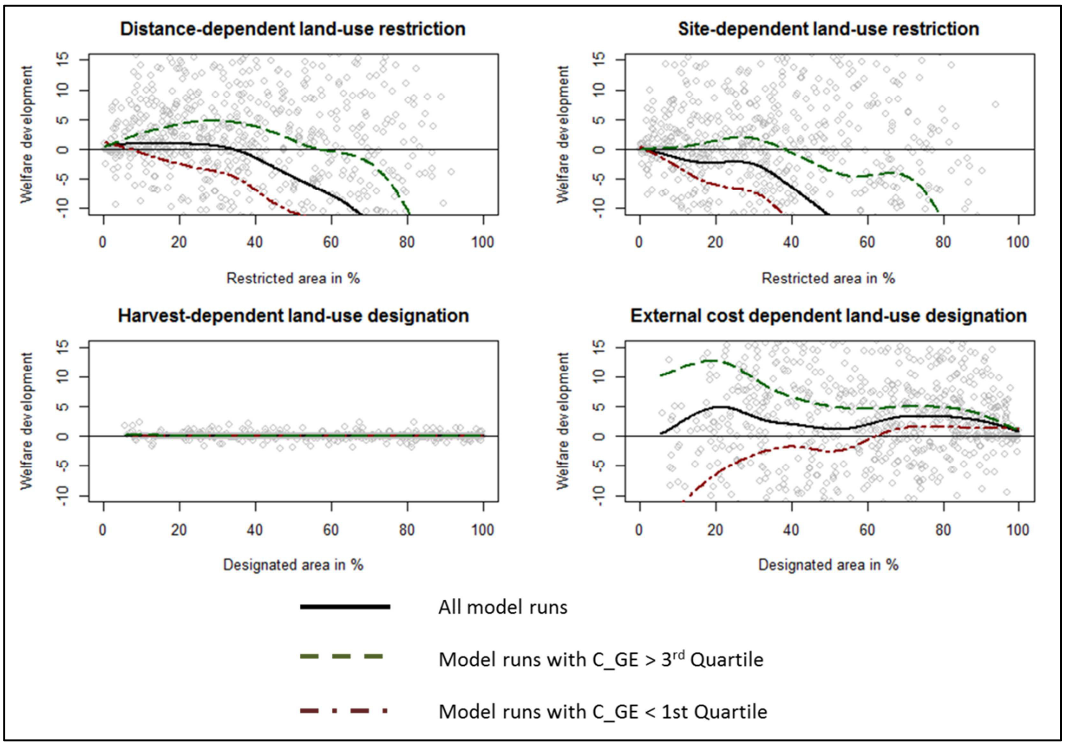


Figure 16: Smoothing splines concerning the influence of regulation-based policy parameters on the efficiency (welfare) depending on the reinforcement costs within the basic model scenario

Fairness

In the following subsection the effect of the regulation-based land-use parameter on the fairness will be examined. Therefore, the *Gini* index, which is based on the regional net utility per capita csx_j of all three consumer centres will be analysed. Again a GAM will be carried out to measure the effect of the increasing regulation-based land-use policy on the Gini index. All p-values of the smooth terms are shown in Table 6.

Once again all policy parameters, except of the harvest-dependent land-use designation parameter are significant under the assumption of a 0.05

significance level. Furthermore, we detect a high dependence on the landscape parameters h_{max}, $x_{s_{max}}$, α (the intensity parameter α determines the initial amount of the distance-dependent external spatial costs), δ (the relations between the aggregated external spatial costs and the business costs will be steered by the parameter δ), the performance parameter l and the parameters m and p_{max} which a relevant to determine the consumer surplus. As fewer power plants lead to a higher concentration the OLS coefficients of h_{max} and l are positive, this means that they have a negative impact on the fairness. The same applies for the parameter m, as high regional revenues can increase the financial gap between regions, assuming a centralized plant allocations. All parameters, which a related to the spatial externalities, have negative OLS coefficients and therefore decrease the fairness gap between the regions if a regulation-based land-use policy is applied.

	Distance		**Site**		**Harvest**		**Spatial Ex.**	
	p-value		*p-value*		*p-value*		*p-value*	
s(*Policy parameter*)	0.021278	*	0.007460	**	0.0960	.	0.000149	***
$s(h_{max})$	0.000610	***	0.000448	***	0.5398		3.16e-06	***
$s(l_{PC})$	1.56e-11	***	< 2e-16	***	0.4991		< 2e-16	***
$s(w_{PC})$	0.331952		0.181980		0.2173		0.163809	
$s(Y_j)$	0.894796		0.649275		0.1099		0.941113	
$s(p_{max})$	0.681581		0.157423		0.3802		0.013461	*
$s(m)$	0.160940		0.002273	**	0.7496		0.000230	***
$s(w_{GE})$	0.204577		0.174267		0.0424	*	0.439881	
$s(x_{s_{max}})$	0.876497		0.005566	**	0.6832		0.278527	
$s(\alpha)$	0.006662	**	0.064391	.	0.3942		0.006634	**
$s(\beta)$	0.315224		0.512947		0.4184		0.981178	
$s(\delta)$	0.000277	***	6.97e-12	***	0.7633		3.51e-12	***
$s(\theta)$	0.408861		0.773405		0.8586		0.529619	

Signif.: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1								
R-sq.(adj)	0.104		0.177		0.0215		0.198	

Table 6: P-Value of the regulation-based policy parameter

In Figure 17 all smooth splines, with their corresponding confidence bands concerning the influence of regulation-based policy parameter on the development of the *Gini* index, are illustrated. Again harvest-dependent land-use designations do not have any effect on the fairness, whereas the other regulation-based land-use policies decrease the *Gini* coefficient at certain restriction or designation levels. In contrast to the efficiency plots the maximum fairness (minimum of the *Gini* coefficient) will be reached at a restriction level close to 70% of the available area for both land-use restriction types, whereas the maximum fairness and efficiency is reached at a similar designation level for external costs dependent land-use designations.

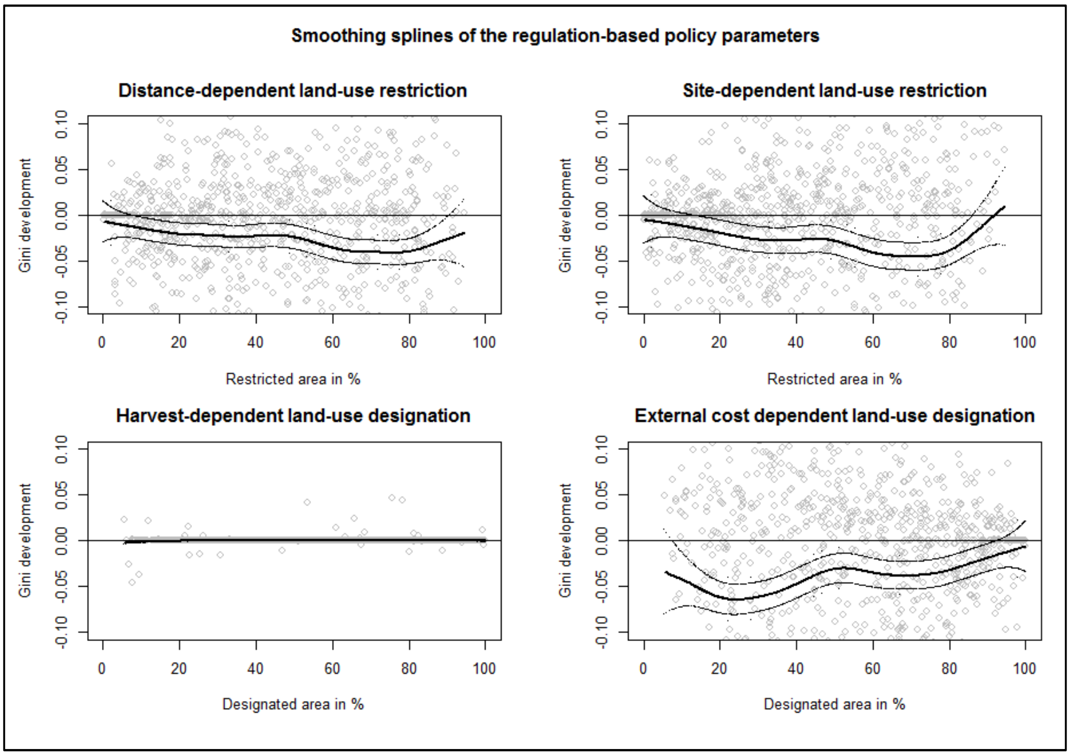


Figure 17: Smoothing splines concerning the influence of regulation-based policy parameters on the fairness

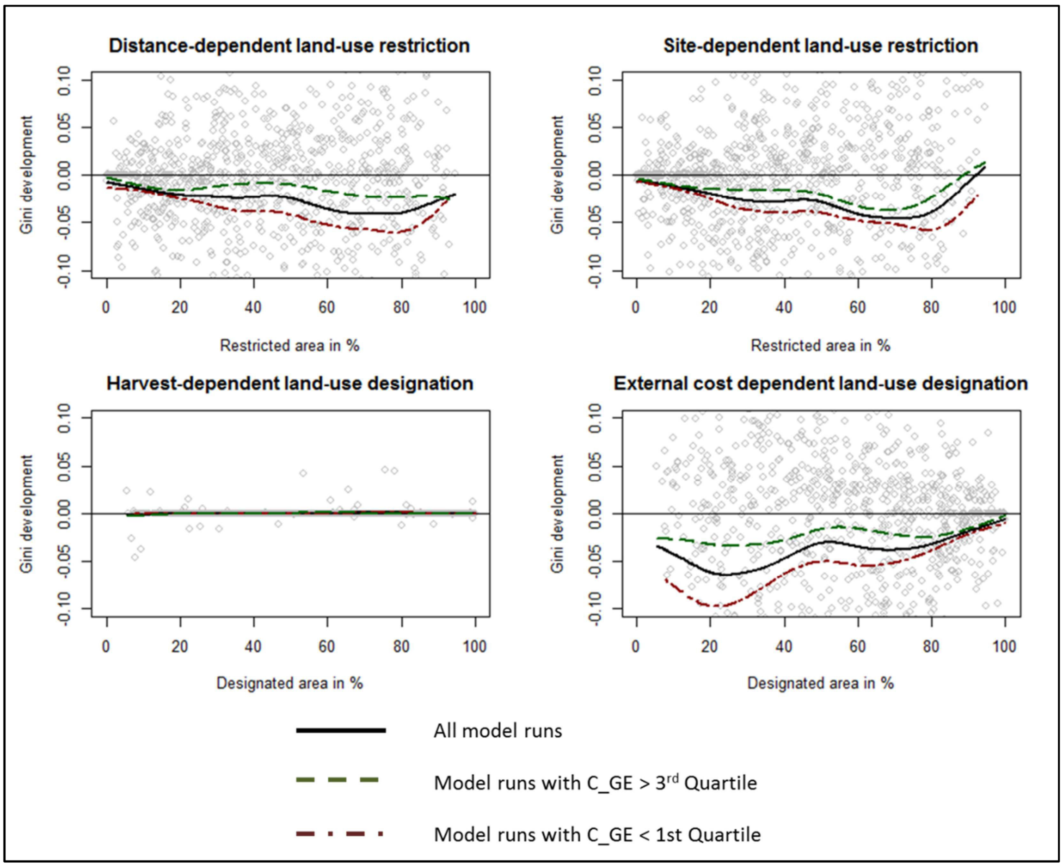


Figure 18 Smoothing splines concerning the influence of regulation-based policy parameters on the fairness depending on initial reinforcement costs

Once more the effect of the regulation-based policy parameters on the fairness, depending on the initial spatial allocation of the power plants at the basic market scenario, have been characterised by a relatively low adjusted R² outcome for all GAMs, illustrated in Table 6. The plots for all regulation-based land-use policies are shown in Figure 18. This time we observe the contrary effect in comparison to the efficiency examination. Therefore, regulation-based land-use policies are more fairness effective if the initial spatial distribution of the RES power plants for the basic market scenario shows a disperse production pattern under the application of the basic policy scenario *Market I*.

4.3 Additional market-based policies

4.3.1 Overview

So far we have focussed on a regulation-based perspective and have determined the impact of land-use restriction and land-use designation policies on the efficiency and fairness of the ABM without taking market relevant factors into account. Accordingly, we will now take a closer look at the impact of market-based mechanisms on the spatial allocation of RES within that section 4.3.

In order to support the deployment of RES the German government introduced the Renewable Energy Support Act (EEG 2000) which has been updated till the latest version of the year 2014 (EEG 2014). The installed mechanism uses various Feed in tariffs (FITs) or market premiums for different technologies in order to guarantee a versified electricity production mix. Feed in tariffs (FITs) are an effective instrument for the deployment of RES. It exist multiple design options with different impacts on the investor risk and spatial allocation impacts (Lesser and Su 2008; Couture and Gagnon 2010).

Generally FITs have been argued to be the most effective support mechanism, due to the high investment security for possible producers. But it also exists difficulties concerning the adaption of the FITs by policymakers (Lesser and Su 2008). One reason is for example the uncertainty regarding future predictions of technology learning rates. Another support mechanism for RES is the market premium which has been introduced in the German renewable energy support act 2012 (EEG 2012) as supplement for the FITs. They can lead to more demand-oriented and flexible RES production patterns (Gawel and Purkus 2013). Therefore, Couture and Gagnon (2010) suggest a support mechanism which integrates the strengths of both systems.

Nevertheless the majority of investors are only motivated to finance RES projects if the expected benefits are at least positive or guarantee an expected positive return. In the case of fixed remuneration rates the total wind power capacity would be concentrated in areas with good wind conditions. In these circumstances the available space strongly depends on the guaranteed subsidies, with the consequence that a high remuneration rate leads to a high rate of available space for potential wind power plants, but at the same time to high windfall profits at areas with very good wind conditions, and vice versa.

However, geographic diversification of a wind power capacity can smooth out fluctuations in wind power generation and can therefore help to enhance system stability (Roques et al. 2010). Grothe and Schnieders (2011) calculated via copula-based analyses optimal wind power allocations regarding the harmonisation of electricity demand and electricity supply for Germany. According to their results the distance between all wind power locations should be maximized which would automatically leads to a decentralised production structure. Furthermore, Elberg and Hagspiel (2015) have found a spatial dependence interrelation between spot price dynamics and wind power locations. Regarding the model results the locational market value for wind turbines depends on the consumer demand and the installed wind mill capacity at an aggregated connection grid point.

At the same time diverse allocation patterns can reduce the demand for grid reinforcements (AGORA 2013) due to a decrease of the distance between the loads and the generations. The geospatial infrastructure model SimWIND by Phillips and Middleton (2012) for optimising wind power generation and transmission in Texas suggests for example that integration cost for renewables due grid reinforcement measures can be reduced by 50% if optimal allocations for new wind power capacities will be considered. However, not only transmission updates can be avoided also the negative externalities considered with distribution infrastructure can be reduced.

Another argument for a less concentrated wind power capacity is the fairness aspect regarding the resulting spatial externalities of the RES due to possible ecological and societal impacts. The design of a market-based instrument together with the determined rules for allocating welfare-relevant costs to the participating agents can have a big impact on the spatial allocation depending on the properties of a defined landscape.

The section 4.3 has the aim to examine the impact of additional market-based policies on the efficiency and fairness within the model framework. For this the basic market scenario *Market I* will be the basis for the comparative analysis. As our ABM does not include the volatility of wind power electricity production, time specific supply fluctuations cannot be specified, but the impact on the overall grid costs, and therefore on the overall welfare, together with the regional fairness can be measured. In the following we will test different variations of a reference yield model (*Referenzertragsmodell*) defined as *Market II* and a producer related takeover of various parts of the reinforcement costs, defined as *Market III*.

4.3.2 The reference yield model

The *Market II* scenario enhances the *Market I* scenario with a reference yield model (*Referenzertragsmodell*), which is part of the Renewable Energy Source act, to determine the compensation for wind mill plants depending on the average wind conditions within certain boundaries. Therefore, the definition of a reference plant, which reflects the average wind condition, is necessary. Wind mills at locations with better or worse wind conditions, in comparison to the reference plant location, get lower or higher average payments for a unit of produced electricity. The general objective of such a policy is on the one hand the avoidance of windfall profits for producers which operate at locations with very good wind conditions and on the other hand to enable the installation of wind mills in regions with less favourable wind conditions.

In the German case study variations are determined via the starting remuneration which is paid at least for 5 years and the basic remuneration which is paid afterwards. The starting remuneration is above the basic remuneration. The renewable energy source act defines, based on the reference power plant, the duration of the higher starting remuneration payment. Based on that information, and the fact that the remuneration is guaranteed for a period of 20 years, an average remuneration tariff per produced electricity unit, depending on the defined reference yield per plant type, can be calculated. In Figure 19 Neddermann (2014) compares for example the average remuneration curves of the EEG 2012 and the EEG 2014. Besides a general decrease of the remuneration, the shape of the curve changed between the two renewable energy source acts as well.

The study of AGORA (2014) makes suggestions concerning a future reduction of the FIT together with an adaption of the reference yield model. One mentioned problem has been the outdated assumption behind the reference plant. Still the EEG defines a reference plant which operates at a hub height of 30 meters. But nowadays wind power plants easily reach a meter hub height of 120 meters. Therefore, an adjustment is necessary.

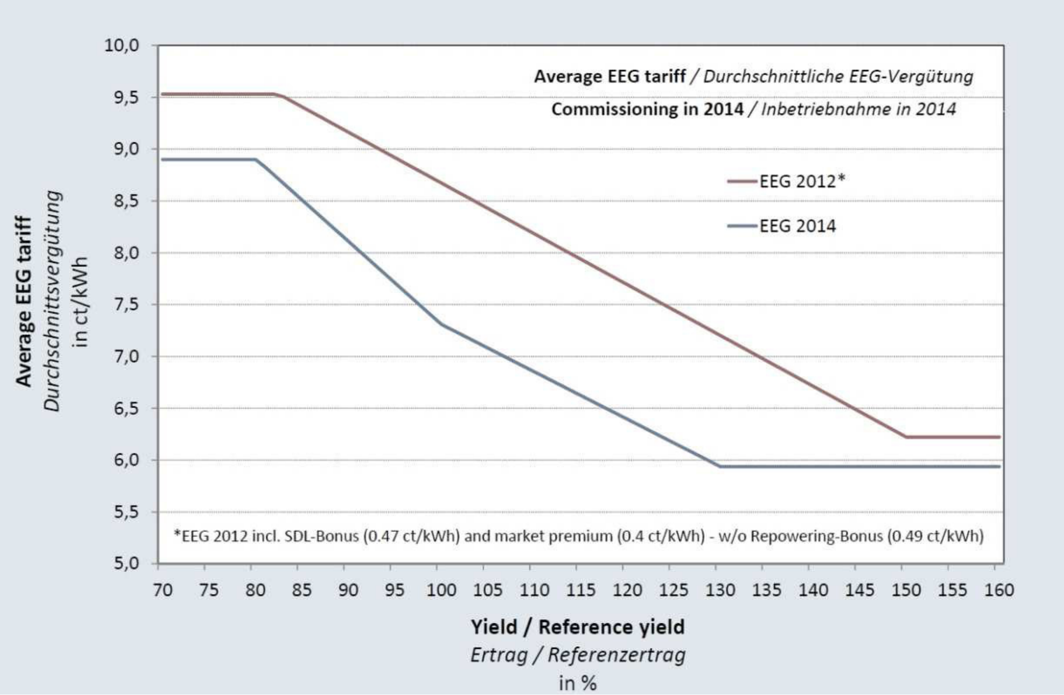


Figure 19: Comparison of average remuneration (without adjustment for inflation) for WT under EEG 2014 and under EEG 2012 (Neddermann 2014)

Within our framework we want to compare different remuneration curves to test their impact on the efficiency and fairness outcomes of the model. Therefore, the site with the average harvest potential $\bar{h}$ of a generated virtual landscape determines the reference site for a model run, in which case $p = 1$. For all other sites of the virtual landscape p differs depending on the reference yield function $f(h)$.

$$p = f(h) = \psi\, h + \omega \tag{23}$$

As $p = 1$ at sites with an average energetic yield potential $\bar{h}$ considering the whole generated virtual landscape, the constant term ω, which determines the intercept of the linear reference yield function $f(h)$, has to be adapted when $\bar{h}$ or the slope parameter ψ differs. The slope parameter ψ regulates the remuneration differences between locations with good wind conditions and locations with bad wind conditions. The parameter will be negative as the average remuneration decreases with an increase of the average wind conditions. Accordingly, the profit function of the producer (6) will be expanded for the policy scenario *Market II* as follows.

$$\max_{y^s, c_n} \pi = f(h) y^s - c_n \tag{24}$$

Again a sample of thousand model runs has been generated. The slope parameter ψ differs randomly within an interval of $[-0.4, 0]$ for every model run. It determines the power of the redistribution policy. Like represented in Figure 19 we additionally test a scenario with an upper and lower boundary for the function $f(h)$.

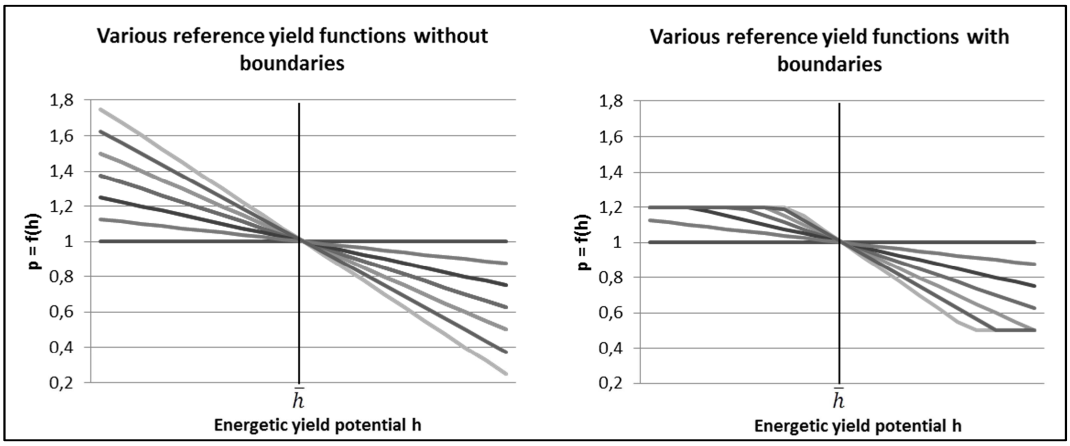


Figure 20: Various reference yield function with different slope parameter ψ

Consequently, p does not fall below 0.5 and does no increase above 1.2. Figure 20 shows various reference yield function with different slope parameters with and without lower and upper boundaries. Corresponding to the previous analysis we compare the resulting efficiency and fairness of the instrument with the pure market based scenario *Market I* to determine the effectiveness of the additional instrument *Market II*.

Efficiency

To estimate the influence of the slope parameter ψ's increase on the overall welfare of a model run, we applied a OLS and a GAM with all basic model parameters and ψ as additional explanatory variable and ΔW as dependent variable. In all cases ψ has been highly significant. As both analyses reveal that a reference yield model has in general a negative impact on the welfare, additional examinations concerning the initial virtual landscape design have been carried out. Like in the previous section 4.2 we analyse the effectiveness of the reference yield model in dependence on the initial plant distribution in the basic market scenario *Market I.* To include the initial spatial distribution of the wind power plants we focus on the resulting grid reinforcement costs C_{GE} of the basic market scenario. If the production capacity is evenly distributed, C_{GE} is close to zero, but if all the capacity is concentrated in one part of the virtual landscape, the grid capacity has to be reinforced in order to guarantee the distribution of the electricity to all three consumer centres, with the consequence that C_{GE} increases.

Therefore, we split the sample for the illustration via smoothing splines in two additional groups. All cases with a C_{GE} value below the first quartile of the complete sample are used for the creation of the red dashed dotted line and all cases with a C_{GE} value above the third quartile of the complete sample are used for the creation of the green dashed line. Consequently, we can compare the effect of an increase of the ψ on the welfare for a concentrated and disperse plant structure within the basic market scenario. Figure 21 shows the described smoothing splines for a reference yield model without and a reference yield model with lower and upper boundaries for the reference function $f(h)$. We see that both models lead to similar results for all three smoothing splines. Furthermore, the reference yield model only seems to be an effective policy concerning the efficiency, if the harvest potential distribution of a virtual landscape would lead to a concentrated production pattern without interference. Nevertheless, that is only the case if the slope parameter ψ does not exceed -0.3.

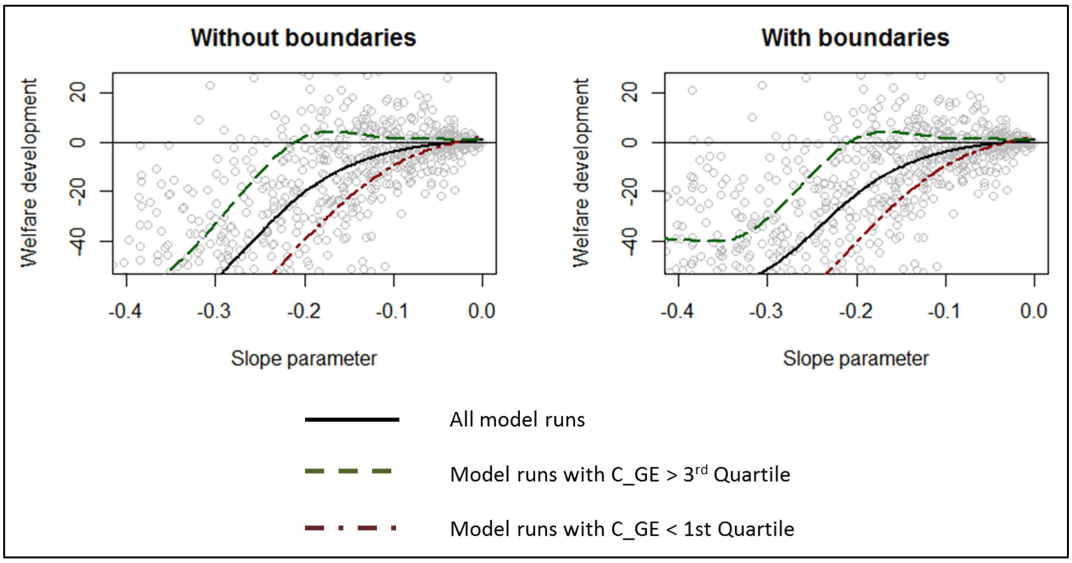


Figure 21: Smoothing splines concerning the influence of the slope parameter ψ on the welfare development Δw

To get more information for the reason of the shape of the welfare development we also examined further components of the general welfare function of the ABM. Consequently, Figure 22 illustrates the development of the producer surplus ΔPS, the consumer surplus ΔCS and the spatial externalities ΔX. In general we observe a concave decrease of the producer surplus and a concave increase of the spatial externalities. Only the consumer surplus affects the welfare positively, mainly due to an decrease of the reinforcement costs C_{GE}. This is the reason why the reference yield model only leads to a welfare increase by high initial reinforcement costs within the basic market scenario. If these costs are low in the initial basic market scenario, the increase of the consumer surplus does not exceed the negative consequences for the other variables of the welfare equation.

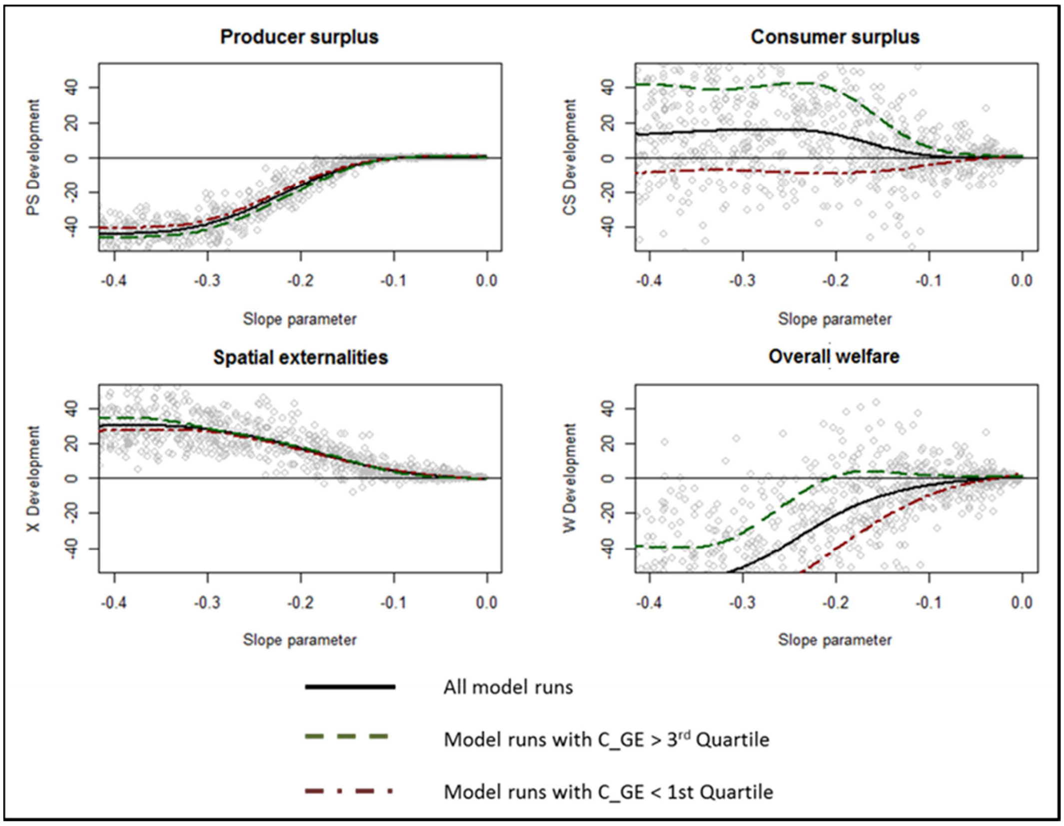


Figure 22: Smoothing splines concerning the influence of the slope parameter ψ on welfare equation elements

Fairness

A similar approach has been applied to the examination of the policy impact concerning the fairness outcomes of the ABM. Once more the development of the *Gini* coefficient $\Delta Gini$ per model run has been calculated to determine the influence of an increase of the reference yield function's slope parameter ψ. The OLS and the GAM with all basic parameters as control variables reveal a high importance of the parameter ψ for the subsample of 1000 model runs.

Like in the previous case, the sample has been separated in three subsamples to examine the effect of the initial plant distribution within the basic market scenario. This time no mayor differences can be identified. The smoothing splines for all subsamples increase with a decrease of the slope parameter. The results reveal that in general the application of a reference yield model leads to a higher *Gini* coefficient and therefore to an allocation which can be defined as less fair.

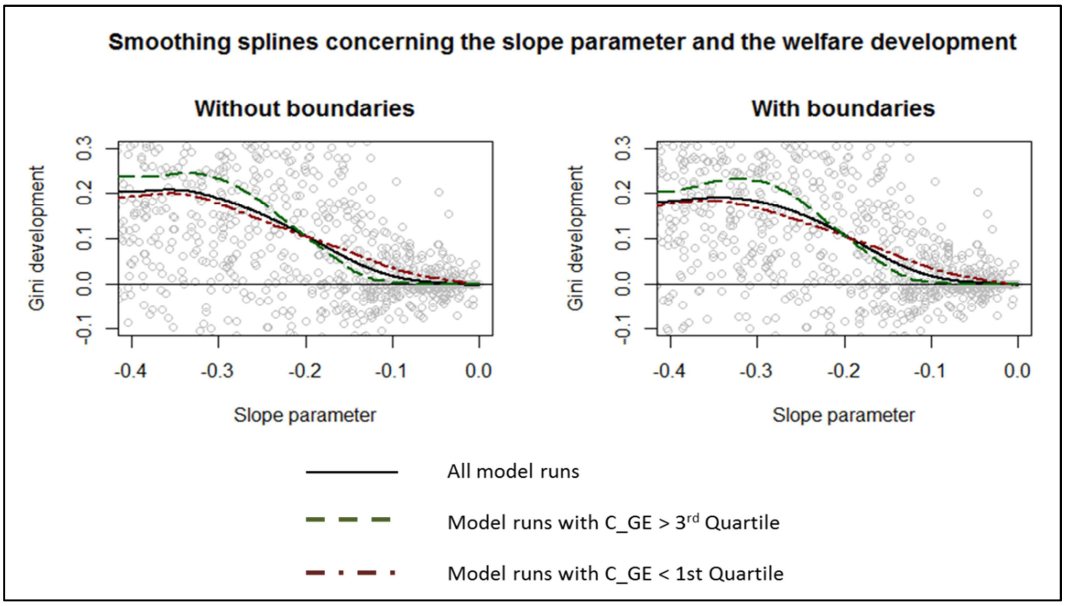


Figure 23: Smoothing splines concerning the influence of the slope parameter ψ on welfare equation elements

Figure 23 shows the three smoothing splines for the reference yield model with and without upper and lower boundaries. That result is rather counterintuitive as production capacity is more evenly distributed. However, if we take the regional net utility development per consumer centre into account we notice a decrease for all consumer centre with a declining slope parameter ψ. Consequently, we observe vice versa a *Gini* coefficient increase.

4.3.3 Reinforcement costs to producer

In the third market-based policy scenario *Market III*, the producers are in charge of paying a certain part of the grid reinforcement costs, therefore certain spatial relevant cost elements will be re-allocated among the participating agents Barth, Weber et al. (2008) have already defined the important grid cost categories together with their reallocation potential. Consequently, we can distinguish between grid connection costs and grid reinforcement costs, whereas the grid connection costs are typically paid by the producer. The grid reinforcement costs which emerge if the grid capacity has to be adapted due to new RES installations are in the most cases paid by the consumer of electricity. Barth, Weber et al. (2008) argue that these costs depend on the connected RES power capacity and the presented structure of the grid, the change of the typical load flow pattern in comparison to the situation with no integration of RES-E power capacity and the impact of connected RES power capacity on power quality and system stability.

In our analysis we focus on the location specific characteristic, accordingly, the initial grid structure and the location specific RES capacity per grid connection point are the dominant factors. Within this framework we are interested in location specific price signals given to RES producer to reduce the grid reinforcement costs considering two different initial grid structures.

The pre-condition for a locational specific effect is that initial generation/load-split, which is in the most cases set to 0/100, has to be changed in favour of the load side, which means that consumer would be relieved form a certain part of the grid costs. Furthermore, this generation specific grid costs have to be locally differentiated in order to provide a signalling effect for further capacity installations.

Two methods which are of further interest are discussed in the literature to address network costs (Faruqui et al. 2009; Brandstätt et al. 2011). Locational electricity pricing (LEP), also known as Locational marginal pricing (LMP), addresses short term price signals, caused by actual network congestion, which implies that only variable cost elements are included. Locational network pricing (LNP) considers long term signals of generation facilities. Therefore, a load flow model is necessary for an ex-post calculation of the regional network prices. An institutional adaptation of the network prices is required from time to time due to the changes regarding the generations, the loads and possible grid reinforcements. The costs can be for both LMP and LNP either node (nodal pricing) or region (zonal pricing) specific which again depends on the applied policy design. Already implemented LMP systems can be found in New Zealand, Australia or California whereas LNP only can be found within scientific discussions (Li et al. 2009).

The improved system efficiency of nodal pricing has already been proven by various authors on the basis of model related analysis for different regional perspective. Leuthold et al. (2005) analysed for example the effect of nodal pricing model while facing additional wind power capacity within a techno-economic framework for the German case study. Lewis (2010) estimated the value of wind energy use together with LMP. He points out that LMP can improve the spatial allocation of wind mills in order to locate generation facilities at sites where the system is signalling a need for them.

In our model we implement an additional parameter ϕ, which determines the share of the reinforcement costs, which a potential producer has to pay, if he decides to install a plant at a certain position. Ex ante the additional reinforcement costs c_{GE_i} for every site of the virtual landscape will be calculated on the basis of defined an additional RES capacity instalment in order to consider long term grid cost signals. Accordingly, the implemented policy simulates the properties of a Locational network pricing (LNP) mechanism Therefore, the producer´s profit function (6) has to be expanded to the following equation.

$$\max_{y^s, c_n} \pi = p y^s - c_n - \phi \, c_{GE_i} \tag{25}$$

The effect of an increase of parameter ϕ on the efficiency and fairness of the model will be examined considering different initial grid situations. Accordingly the initial conventional plant configuration, and consequently the grid capacity of the grid segments, will differ. We distinguish between the configuration *A* and *B*. The first configuration *A* equals the basic grid situation (described in detail in section 2.4.3), whereby a single conventional power plant produces the whole electricity for the three consumer centres.

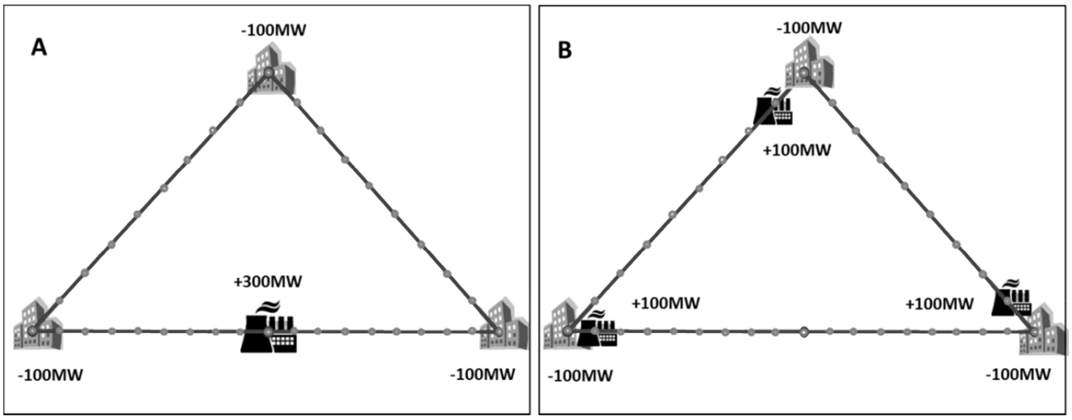


Figure 24: Initial conventional plant configuration A and B

On the contrary, in scenario *B,* every consumer centre provides its own electricity with a conventional plant at the next adjacent connection grid point. The conventional electricity feed-in reduces with the similar amount of the new feed-in of the constructed RES energy plant depending on the initial conventional power capacity. Figure 24 illustrates both initial grid scenarios.

Efficiency

In order to analyse the cost structure comparability of both initial conventional plant configurations, the distribution of the reinforcement costs C_{GE} within the basic market scenario has been illustrated via two density plots in Figure 25. Besides the distinct shapes of the density curves differences in the mean values and standard deviations within both samples can be identified. In general, the mean value of the initial plant configuration B is with 20.37 nearly 40% lower than the mean value of A with 33.16. These results are a first indication for a lower vulnerability concerning reinforcement costs of the initial conventional plant configuration B when facing a concentrated harvest potential of a renewable energy source within a defined region.

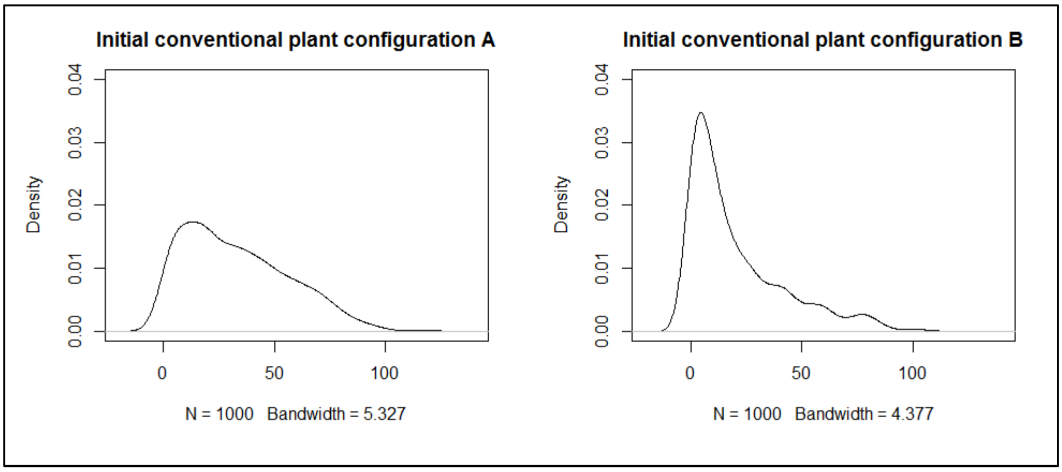


Figure 25: Density plots of the reinforcement costs of both generated samples

At the beginning we prove the significance of the results with a OLS and GAM by using, besides the policy parameter ϕ, all basic parameters as further control variables and the welfare development Δx as dependent variable. For both initial grid configuration scenarios the policy parameter ϕ, which determines the producer reinforcement cost share, is highly significant. The positive OLS coefficient of ϕ also reveals the positive impact of such a policy on the overall welfare.

As both samples are not identical we focus on the reinforcement costs differences within the basic market scenario for further analyses. Therefore, the two samples have been separated in three groups: (I) First only the samples with reinforcement costs below the first quartile of the complete sample are used for the construction of the red dashed dotted smoothing spline, (II) second all values are used for the construction of the black smoothing spline, and (III) third only the values above the third quartile are used for the construction of the green dashed smoothing spline.

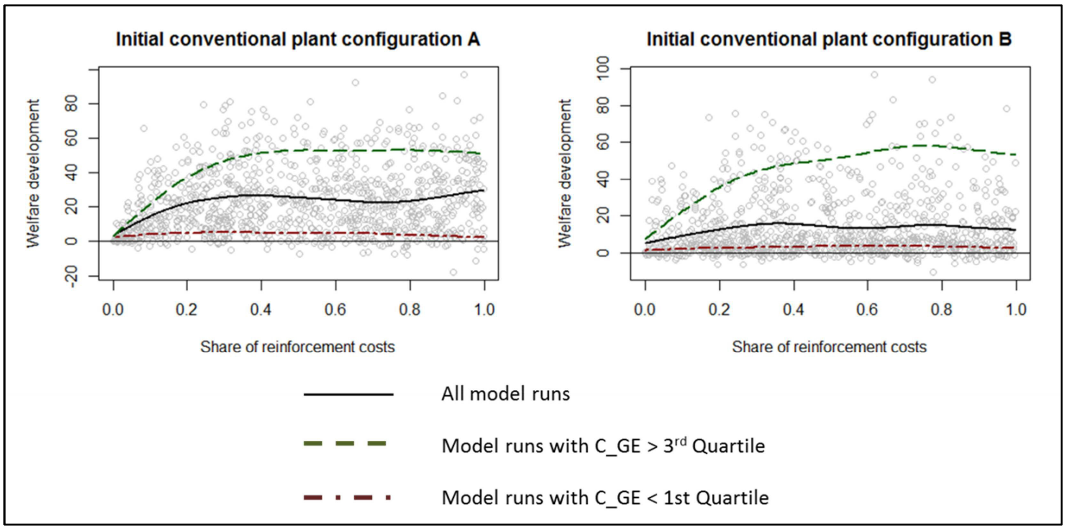


Figure 26: Smoothing splines of the welfare development concerning the grid policy parameter for both initial conventional plant configuration A and B

The results of the dashed smoothing spline are similar, despite small differences concerning the extreme value of the subsample above the third quartile. Like in the previous cases the amount of the initial reinforcement costs are important for the efficiency impact of the policy, which can be determine due to the differences of the maximum values of the three curves. The general slope of all curves reaches its maximum close to 20% share of the reinforcement costs. Therefore, a small share can have already a big positive impact on the welfare development. If we assume that the reinforcement costs of the ABM can be split into a fix and a variable cost component, it would be enough to implement locational electricity pricing in the current setting, which addresses a short term price signal due to congestion problems of the grid infrastructure (LMP). The smoothing spline results are illustrated in Figure 26. The majority of the positive welfare effect can be explained with the reinforcements cost reductions due to more evenly distributed wind power plants, which vice versa lead to more balanced grid load flows. Despite the positive impact on the consumer surplus because of lower reinforcement costs, the producer surplus is affected negatively. The power of the negative impact strongly depends on the overall efficiency loss of the electricity production facilities. For homogenous landscape settings with evenly distributed harvest potential (wind conditions) the effect is smaller in comparison to heterogeneous landscape settings with high site specific concentration of areas with favourable harvest conditions.

Fairness

After the application of OLS and GAM with all basic parameters as further control variables and the development of the *Gini* coefficient as dependent variable, we cannot identify a significant effect for an impact of the parameter ϕ on the fairness outcome.

Consequently, the integration of a locational electricity pricing (LEP), also known as nodal pricing, or locational network pricing (LNP) wouldn't have any effect on the fairness outcomes under the taken assumption of the ABM framework.

4.4 Summary and conclusion

In this chapter 4 the different policy scenarios have been evaluated concerning their efficiency and fairness impact. Therefore, regulation-based and additional market-based policies have been distinguished. The ABM framework has been extended in order to guarantee the policy application and the following impact evaluations. For the examination of the generated Monte Carlo Simulation samples a statistical approach based on the computed rate of changes after the policy implementation has been used which has been introduced in chapter 3.

In a first step, the regulation based policies have been evaluated. A differentiation between land-use restriction (*Regulation I*) and land-use designation (*Regulation II*) measurements has been carried out, whereas a land-use restriction can be distance- or site dependent and a land-use designation can focus on the harvest potential or on locations with a small amount of spatial externalities.

The results reveal that distance-dependent land-use restriction policies have a positive efficiency effect at a moderate restriction level (around 25% restricted cells). But the maximum fairness effect of such measurements will be reached by a higher restriction rates (>70% restricted cells). Site-dependent land-use restrictions only have a positive influence on the efficiency at a moderate restriction level if the initial distribution of the RES power plants has been highly concentrated. In such a case the producer surplus decrease is below the spatial external costs decrease. Harvest-dependent land-use designations do not have any effect on the fairness nor on the efficiency, whereas external cost-dependent land-use designations are the most effective policy concerning efficiency and fairness. However, all results are highly dependent on the initial spatial pattern of the RES power plants at the basic market scenario. Highly concentrated spatial RES power plant patterns strengthen the efficiency effectiveness but weaken the fairness effectiveness of the regulation-based land-use policies.

Moreover, an efficiency fairness trade-off for the application of influential regulation-based policies has been observed. The main reason is that efficiency and fairness improvements come at different regulation intensities. This finding is consistent with the economic literature while more regulation or planning leads to an efficiency decrease whereas the societal fairness increases.

Of course land-use decisions in the real world are much more complex than it has been shown within the ABM framework. Nevertheless enough space for RES has to be guaranteed to stabilise the welfare of the general system whereas a complete absence of any land-use policy would lead to a chaotic proliferation of RES. Furthermore, a high concentration of all wind mills in one area of the virtual landscape does not only effect the fairness in a negative way, but also the efficiency of the overall system can suffer from such a spatial electricity production pattern.

In a second step additional market-based policies have been applied within the existing ABM framework. More precisely a remuneration scheme with a reference yield model (*Market II*) and the re-allocation of grid reinforcement costs from the consumer to the producer (*Market III*) have been tested. Based on the results one can argue that the design of the reference yield model determines the efficiency and fairness impact of such a policy. Despite a small impact of the existence of lower and upper reference yield boundaries, a significant importance of the slope parameter arrangement has been detected. That is reasonable as the slope parameter determines, in the case of wind power, the support in dependence of the local wind condition. If the slope parameter falls below a certain value, the possibility for a decrease in the welfare significantly increases, as the incentive increases to build new RES capacities within areas with poorer wind conditions, which leads vice versa to lower average electricity outcomes per plant. Consequently, more RES plants have to be built to supply the similar demand with the risk of higher spatial externalities. Likewise an average fairness decrease can be observed at the same time.

Additionally, the initial plant distribution has a significant impact on the efficiency effectiveness of the reference yield policy. Therefore, we can determine that the efficiency effectiveness increases with an increase of the reinforcement costs C_{GE} within the basic market scenario. But the effect is negligible for the determination of the fairness parameter's development. The results reveal that the integration of a reference yield model within a remuneration scheme has a positive efficiency impact if the natural endowments of a renewable source (wind conditions) are unequally distributed within an examined region. However, the results have also illustrated a resulting fairness decrease measured by a *Gini* coefficient increase.

The policy scenario *Market III* has a direct impact on the grid reinforcement costs of the ABM by increasing the producer's responsibility for a better site assessment, which takes grid externalities into account. In comparison to other tested policy scenarios, it has the highest positive impact on the efficiency of the model. Good improvement can already be achieved by making the producer responsible for 20% of the arising reinforcement costs if this cost a site-specific. This amount leads to different plant locations, which significantly decrease the reinforcement costs. At the same time the policy does not significantly affect the fairness outcomes of a model run. Therefore, it can be applied without facing any risk of capital redistribution. Also the effect of different initial conventional plant configurations has been tested with the result that decentralised conventional systems generally lead to lower reinforcement costs. Consequently, they are initially better prepared for the shift to a renewable energy production than centralised systems.

Due to the high welfare increase by a relatively low share of the reinforcement cost parameter φ, we can assume that an LNP mechanism, that also takes the fix reinforcements grid costs into account, would be an adequate policy from a pure efficiency perspective. However, the implementation of a new policy framework leads to high transaction costs, which can even increase further if locational based grid costs have to be frequently adapted.

Chapter 5

The role of the regions

Lessons from the cooperative game theory and the ABM

5 ***The role of the regions - Lessons from the cooperative game theory and the ABM***

5.1 Overview

So far all model analyses have been carried out under the assumption of an applied cooperative strategy by all consumer centres. Therefore, all regional participants have worked together in a grand coalition to obtain the objective of a 100% renewable power generation within a landscape while maximizing the overall welfare under different policy conditions. Nevertheless this cooperative strategy does not automatically lead to the *optimal* individual outcome for every consumer centre. From a model perspective it might be the case that only one consumer centre faces the risk of negative spatial externalities because of favourable wind conditions within its regional boarders, or only one consumer centre benefits from the transformation process through increasing tax revenues. Consequently, a self-sufficient strategy, under the precondition that a region supplies its own demand, can lead to a higher regional net utility in comparison to a cooperative strategy, depending on regional preferences and the physical endowment of the consumer centre's catchment area.

The theoretic fundament for the cooperative and non-cooperative strategies of agents has been carried out by Neumann and Morgenstern (1944) developing the theory of games and economic behaviour. Osborne and Rubinstein (1994) distinguish coalition models from non-cooperative models by focussing on the group achievement instead of the individual player's possibilities. Furthermore, cooperative game theory does not specify a game through a strategic environment, including the order of moves, the set of actions at each move, and the payoff consequences relative to all possible plays, but instead, it reduces this collection of data to the coalitional form (Winter 2002). As the grand coalition is a basic assumption for the cooperative game theory and a potential result for the non-cooperative game theory (Selten 2001), the cooperative game theory focusses on the division of the payoffs among the coalition members by using methods like *the Shapley Value* (Shapley and Roth 1988). Saad et al. (2009) define games as coalition formation games which violate the basic assumption that the grand coalition is always beneficial. Costs can arise during the coalition formation process. In the case of the implemented ABM framework grid externalities and spatial externalities can support the partition from the grand coalition out of a consumer centre's perspective.

Uncooperative strategies are already visible in the context of the energy transition in Germany. For example the federal government of Bavaria has modified its Bavarian building code (BayBo 2014) to increase the distance from future wind mills to the closest settlement up to ten times (10-H-Abstandsregelung) of the wind mill's hub height (§ 82 and § 83 BayB). Accordingly, wind mill installations within the defined exclusion buffer are not approvable, which leads to a significant decrease of potential areas for the production of wind energy (BMU 2013). Moreover, the observed delay, regarding the construction of a grid system to strengthen the north-south connection according to a network developing plan (BnetzA 2013), indicates the high preferences for the protection against spatial externalities in Bavaria. At the same time the new expansion path (*'Ausbaukorridor'*) for RES, which has been adopted in the latest Renewable Energy Sources Act (EEG 2014), can lead to a competition concerning the construction of new RES capacities between economically interested federal states. Consequently, we have to deal with multiple regional interests which vice versa lead to various strategies concerning the transformation process of the energy system within the federal system in Germany.

The chapter's objective is to soften the basic grand coalition assumption of the ABM model and to establish a framework to analyse the coalition formation process among the three consumer centres to answer the following questions: Which coalition form guarantees the highest cooperation benefits considering homogeneous and heterogeneous landscapes and consumer structures? What happens with the efficiency and the fairness of the entire landscape if consumer centres start with the implementation of regional instruments to follow their own strategic interests in order to increase their individual benefits considering homogeneous and heterogeneous landscapes and consumer structures?

Accordingly, in a first step all possible coalition options will be examined regarding their impact on the model's efficiency and fairness to obtain the *optimal* coalition structure together with the resulting cooperation benefits. Consequently, we will focus on the average of particular welfare components considering the entire landscape.

Afterwards consumer centres are allowed to implement regional instruments to follow two different strategic orientations in order to increase their individual benefits. So in this part the emphasis lies on a consideration of the impact on particular welfare components, as well as on the individual perspective of the consumer centres. Therefore, a regional economy encouragement strategy (focusing on an increase of the regional economic welfare effect coming from RES) and spatial externality avoidance strategy (focussing on the minimization of negative spatial related consequences caused by RES) will be introduced. Again both model extensions will be tested under the assumption of homogenous and heterogeneous landscapes and consumer structures.

5.2 Lessons from the cooperative game theory

In the precedent chapters 3 and 4 all analyses have been carried out with the basic assumption of an established grand coalition. This assumption is plausible as all three consumer centres are a part of a higher administration unit together with their corresponding regional catchment areas. Nevertheless the German experience has shown that federal states are also determined by un-cooperative behaviour when it comes to negative regional externalities due to the adopted energy transition process. Before we want to revoke the grand coalition assumption some basic concepts of the cooperative game theory will be introduced in a form of the coalition game. Afterwards we will prove that it is possible to apply cooperative games in the case of the ABM.

A coalitional game with transferable payoffs consists of a finite set of players N indexed by i; and a function v that associates with every nonempty subset S of N (a coalition) a real number $v(S)$ defined as worth of S that the coalition members can distribute among themselves. Furthermore, we assume $v(\emptyset) = 0$ (Neumann and Morgenstern 1944). Another typical assumption is the idea that a coalition is always beneficial for the participants. The concept is called a superadditivity and is defined as

$$v(S_1 \cup S_2) \geq v(S_1) + v(S_2)\text{ , s.t. } S_1 \cap S_2 \tag{26}$$

Saad, Han et al. (2009, p. 4) describe the concept as follows:

> “[…] a game is superadditive if cooperation, i.e., the formation of a large coalition out of disjoint coalitions, guarantees at least the value that is obtained by the disjoint coalitions separately. The rationale behind superadditivity is that, within a coalition, the players can always revert back to their non-cooperative behaviour to obtain their non-cooperative payoffs. Thus, in a superadditive game, cooperation is always beneficial. Due to superadditivity in canonical games, it is to the joint benefit of the players to always form the grand coalition N, i.e, the coalition of all the players, since the payoff received from $v(N)$ is at least as large as the amount received by the players in any disjoint set of coalitions they could form. […]”.

Under such a defined setting the only question which is of further importance is the division of payoffs among the members of the grand coalition.

There are already manifold coalition games in the context of the electricity system’s organisation. Some authors focus on the distribution of grid costs among regions. By applying a variety of probabilistic cooperative games, Bhakar et al. (2010) produce stable and consistent results for the cost allocation of power networks. Contreras et al. (2009) present an incentive scheme by viewing each potential investor as a player to encourage investments in transmission capacities. Hasan et al. (2014) already focus on the integration of large scale remote renewable power generation into the grid during the cost allocation mechanism. Likewise, other authors have applied cooperative game designs in the context of wind power and nodal pricing. Bitar et al. (2012) and Baeyens et al. (2013) have explored the effect of the cooperation's impact on producers' benefit in the context of aggregate power output variability obtainable through geographic diversity. Moreover, cooperative game theory has been used for the problem of sitting noxious facilities (Kunreuther et al. 1987; Lejano and Davos 2002) which are related to the NIMBY debate illustrated in chapter 1.

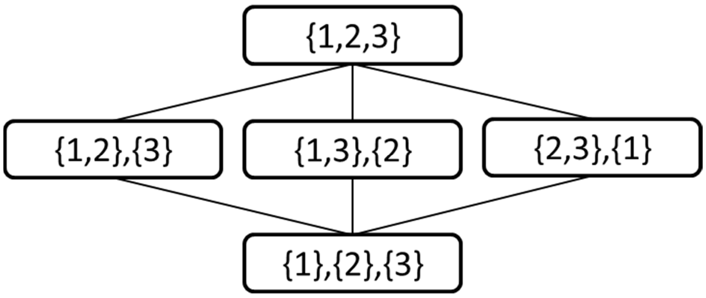


Figure 27: The coalition structure graph for three agents

In the majority of the above mentioned game analyses classical divison methods like *the shapley value* or *the core* have been applied. Osborne and Rubinstein (1994, p. 257) describe *the core* as follows:

> "*The core* is a solution concept for coalitional games that requires that no set of players be able to break away and take a joint action that makes all of them better off."

Above that *the shapley value* method considers the axioms of efficiency, symmetry, dummy and additivity and therefore guarentees a unique result for the divison problem.

But before we can use similar techniques for our problem, we have to show that the basic assumptions of coalition games will not be violated by the ABM framework. We have to compare the outcomes of the possible consumer centre coalitions with each other. Figure 27 shows the coalition structure graph of a game with three agents. As we have to deal with three consumer centres, five model runs with all coalition options and an identical parametrisation have to be executed. At the top of the graph we find the grand coalition whereas the bottom is represented by a total split of all game participants.

In the case of the grand coalition a new producer can pick any site which maximizes its individual benefit. If the final condition $Y^S \geq Y^D$ of the ABM is met, the transition process is completed. According to the cases $\{1\}, \{2\}, \{3\}$, where every consumer centre provides electricity on its own, the final conditions change to the equation (27). Therefore, every consumer centre J meets its own demand with RES within its catchment area.

$$\mathrm{Y}_j^D \leq \mathrm{Y}_j^S \tag{27}$$

Nevertheless, the connection between the consumer centres via the existing grid structure remains active. Despite not considering volatile aspects of the RES within the model, an increasing importance of an improved grid structure concerning the connection of different regions can be observed during the energy transition process. This is especially important if regional peak loads have to be balanced under unstable weather conditions, which do not guarantee the similar regional amount of electricity supply. Accordingly, it does not make any sense to focus on isolated supply structures. However, to include the special role of the grid infrastructure we create two different samples. The first one neglects the resulting grid reinforcement costs C_{GE} and the second one takes them into account. Consequently, w_{GE} equals zero for the first sample. Like in the previous chapter 4 we run the 1000 Monte Carlo simulations with a basic model parameter variation of +/-20% to get a robust sample. Within every model run all possible coalition options, illustrated in Figure 26, will be carried out. Finally the mean values of the overall welfare W, the producer surplus PS, the consumer surplus CS and the spatial externalities X for the entire landscape will be calculated.

In the following Figures 28 and 29, all average outcomes of the overall welfare components are plotted. Accordingly, the grand coalition leads to the highest welfare results if grid reinforcement costs have been neglected. We see that the producer surplus decreases with a decrease of coalition participants. The producer choice is restricted within smaller coalitions, consequently, the availability of efficient sites decreases.

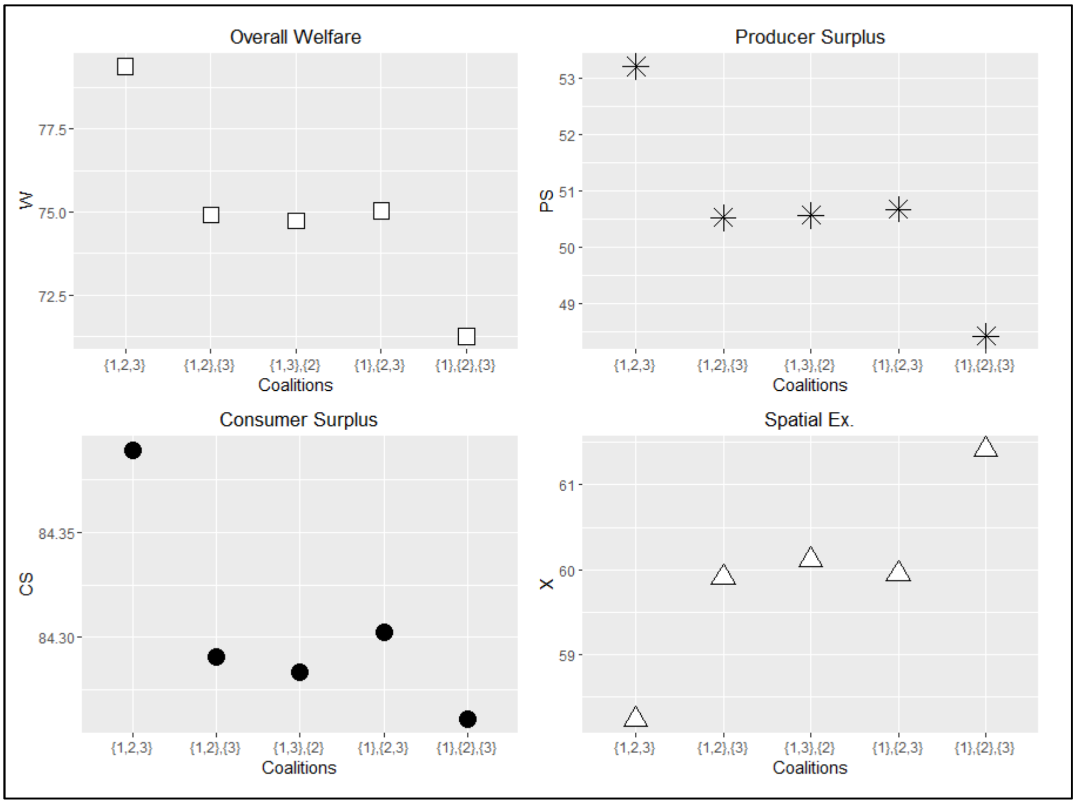


Figure 28: Average total outcomes of welfare components per coalition type without reinforcement costs

At the same time, the spatial externalities increase with a decrease of coalition members, which even enhances the significance of cooperation among the consumer centres. Due to the small variation of the consumer surplus outcomes between the possible coalition options, the welfare impact of the consumer surplus is minimal. In general we see that cooperation is beneficial in an ABM setting without any grid reinforcement costs. Accordingly, the given definition of superadditivity in equation (26) has not been violated with the result that a grand coalition always leads to best model outcomes and has therefore the highest coalition value.

Things change if we add grid reinforcement costs to the analysis. After the examination of the second produced sample we get a different picture regarding the welfare outcomes of the possible coalition options in comparison to the first sample. Now the uncooperative case (where every consumer centre supplies its own demand) has the highest average welfare outcomes. This time, the producer surplus decreases and the increase of spatial externalities will be compensated by an increase of the consumer surplus with the consequence that the superadditvity assumption has been violated. The main reasons are the resulting grid reinforcement costs by dealing with centralised RES production structures, which vice versa leads to a consumer surplus decrease. As the risk of high grid reinforcement costs is significantly lower if every consumer centre meets its own demand with RES within its catchment area, the uncooperative case produces the highest average welfare outcomes. Accordingly, we can say that high grid reinforcement costs support uncooperative behaviour and can be defined as coalition formation costs.

Because of the samples’ evaluation results we cannot apply standard game theoretical division methods to analyse the coalition structure by taking all cost categories of the ABM into account. Therefore, we apply a heuristic approach to analyse the regions’ reaction on the transformation process of the electricity system.

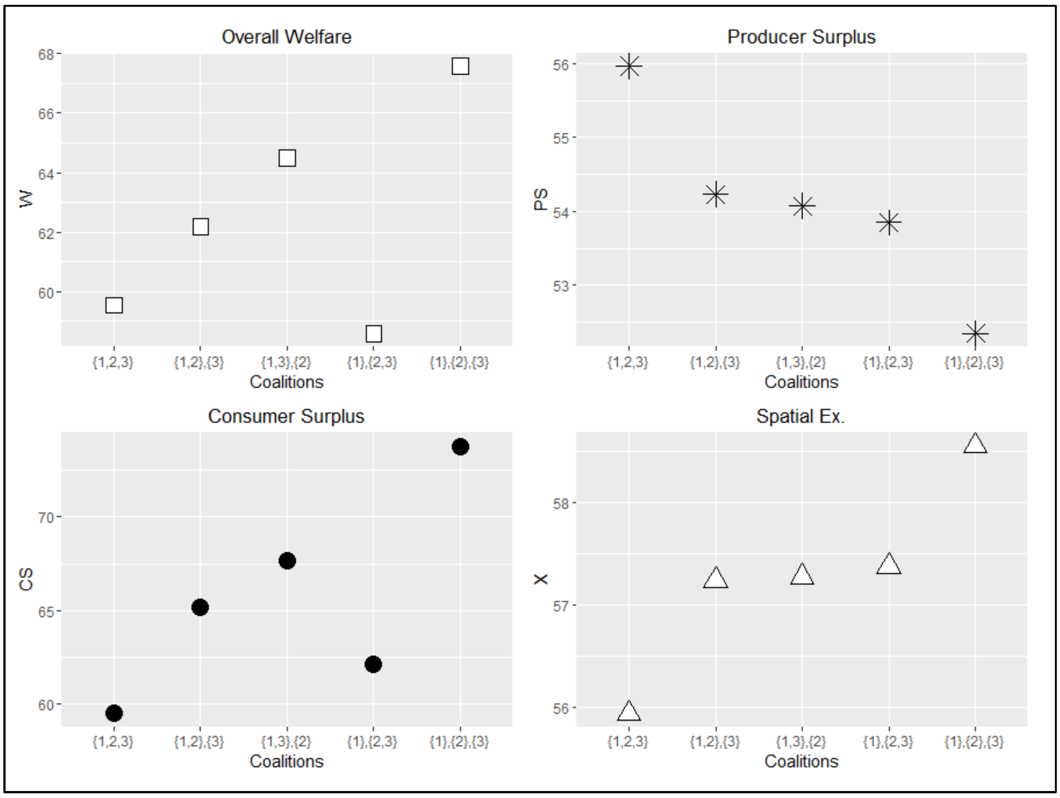


Figure 29: Average welfare equation outcomes per coalition type including reinforcement costs

5.3 The regions’ reactions on the transformation process

5.3.1 Overview

If the superadditivity assumption is violated, which is the case for the spatial allocation problem of RES, the grand coalition is in most of the cases not the optimal solution for the entire landscape. Under this circumstance an extension of our cooperative perspective to an additional individual point of view is necessary. The property of coalition structures and their adaptability to environmental variation or existing externalities (Saad, Han et al. 2009) are important.

One opportunity under such a setting is the implementation of split strategies and merge strategies. Apt and Witzel (2009) have presented a mathematical framework to construct a coalition formation algorithm. Therefore, simple rules for forming or breaking coalitions and well-defined stability assessment have to be introduced which can be based on individual preferences. Rahwan et al. (2015) provide an overview on developed algorithm and heuristics in the context of coalition structure generation, which all strongly depend on the purpose of the game.

In the case of the energy transition process it cannot be realistic to apply a simple regional split strategy, as an unconnected region would not be able to supply its own electricity demand out of RES at any time. Regional weather fluctuations would endanger the supply security and therefore the whole energy transformation process. Accordingly, we have decided to take the grand coalition as initial starting condition $S = (\{1,2,3\})$, which refers to the beginning of the energy transformation process with harmonised regional policies without any local avoidance planning or regional support strategies. To address the increased regional importance during the energy transformation we enhance the model complexity by allowing the implementation of particular regional strategies which can either encourage the deployment of RES capacity in order to increase the regional economic welfare effect from RES, or which try to avoid new RES installations because of spatial externality concerns. Consumer centres can from now on implement such strategies if the assumptions for the behavioural shift are met.

To evaluate the strategies, we take the resulting regional welfare (28) and the regional net utility (18) for every catchment area besides the overall efficiency and the fairness into account.

$$W_j = PS_j + CS_j - X_j \tag{28}$$

5.3.2 Spatial externality avoidance strategy

The spatial externality avoidance strategy defines a situation in which a region is no longer willing to accept more RES installations within its defined catchment area due to an increase of spatial externalities above a defined maximum (29) which is related to the initial welfare level at the beginning of a single model run. Accordingly, the defined strategy strongly focusses on the societal and ecological aspects of the energy transformation process.

$$if\ X_j > \lambda W_j^{t=0} \tag{29}$$

To slow down the deployment of new RES capacities an additional regional instrument in form of a tax will be implemented within the catchment area of a consumer centre if a critical spatial externality level has been reached.

$$\pi_i = \begin{cases} py^s - c_n - \tau & if\ \ i\ \in J\ and\ \ X_j > \ a \\ py^s - c_n & otherwise \end{cases} \tag{30}$$

Consequently, the benefit function of the producer (30) will be adapted if the instrument implementation condition will be met. Note that due to an increase in transaction costs (regulation process, delay in permissions), the tax doesn´t lead to an increase of the consumer surplus for the affected consumer centre J. The tax represents new regulation barriers during the permission process which slows down the planning and installation of new capacities. Accordingly, the producer´s planning costs increase which vice versa decreases the benefits of the producer. Another opportunity is the implementation of drastic land-use regulations which are comparable to very high tax levels leading to negative benefits for the producers with the consequence of a total installation stop within the catchment area of a consumer centre.

5.3.3 Regional economy encouragement strategy

In contrast to the spatial externality avoidance strategy, the regional economy encouragement strategy seeks for more investments within its catchment area in order to benefit from the regional multiplier effect of RES due to an increase of tax revenues and potential maintenance jobs. The negative spatial externalities produced by RES are not considered during the strategy implementation procedure, as the consumer centre preferences for ecological and societal protection of the decision makers are very low. Consequently, the strategy will be applied if the welfare minus the spatial externalities fall below a defined value (31) which is again related to the initial welfare level before the model starts to add RES capacity.

$$if\ W_j - X_j < \gamma W_j^{t=0} \tag{31}$$

Accordingly, the consumer centre reacts with the implementation of a regional specific subsidy beside the guaranteed price for a unit of produced electricity (32). Therefore, new RES producers receive an extra payment if they build their plants within the catchment area of the particular consumer centre.

$$\pi_i = \begin{cases} (p + s_j)y^s - c_n & if\ \ i\ \in J\ and\ \ W_j - X_j < b \\ py^s - c_n & otherwise \end{cases} \tag{32}$$

The subsidy vice versa reduces the consumer surplus (33) of the consumer centre, which means that the regional economy encouragement strategy can only be beneficial for a consumer centre if the multiplier revenues exceed the issued subsidies due to an increase of the locally added value because of RES.

$$CS_J = \begin{cases} CS_J = Y_J^D \dfrac{p_{max} - p}{2} + mY_J^S - \dfrac{Y_J^D}{Y^D} C_{GE} - S_J & if \quad W_j - X_j < b \\ CS_J = Y_J^D \dfrac{p_{max} - p}{2} + mY_J^S - \dfrac{Y_J^D}{Y^D} C_{GE} & otherwise \end{cases} \tag{33}$$

5.4 Lessons from the ABM framework

5.4.1 Overview

Like in the previous impact evaluation we applied 1000 Monte Carlo simulations using the illustrated basic parameter intervals of section 2.7.2 together with the presented spatial externality avoidance and regional economic encouragement strategy scenarios and a business as usual (BAU) scenario to examine potential differences between the three scenarios per randomised defined parameter setting. For every Monte Carlo Simulation the tax level τ, the subsidy level s and the strategy decision parameters γ and λ have been randomly selected on the basis of defined intervals [0,1] for every parameter.

Consequently, we can measure their impact on the model outcomes at the end of the simulation via a sensitivity analysis to observe potential thresholds. All model runs which did not match the defined plausibility criteria have not been considered. The chosen interval makes sense as the basic price per demand unit is 1. Therefore, the maximum tax or subside cannot be higher than 100% of the basic price for the simulation. In the case of a strategy decision parameter γ above 1, every consumer centre would immediately choose the regional economy encouragement strategy at the beginning of a single model run. Finally we can argue that no consumer centre will choose the spatial externality avoidance strategy if the critical externality level is set too high due to a strategy decision parameter λ above 1.

5.4.2 Strategy impact on the central welfare components

In the following general observations will be illustrated after the examination of the average overall welfare, producer surplus, consumer surplus and spatial externality outcomes. They are shown in Figure 30. The overall welfare increases due to the application of b. One reason is the increase of the consumer surplus due to a reduction of the grid externalities by more than 18% on average. Therefore, a concentration of the wind mill installations is less likely having a homogenous setting. Accordingly, the application of the presented strategies can favour more decentralised production patterns in comparison to the business as usual scenario.

However, the producer surplus decreases in the case of the implementation of regional tax because of a decrease of sites with high benefits for the producer, which leads to an average efficiency decrease for all wind mill installations. In the case of the regional economy encouragement strategy the average remuneration per plant increases due to additional regional support. Because of the paid subside the average consumer surplus increases with a minor intensity in comparison to the spatial externality avoidance strategy. In general we see that spatial externalities have a minor importance in an average examination. That does not mean that the spatial externalities are not affected by the strategy shift, it rather means that the direction of the influence remains unclear, as an increase as well as a decrease of the spatial externalities per single model run is possible in dependence on the generated virtual landscape setting.

In the following we examine the importance of the reinforcement costs closer, by splitting the sample into two further groups. The first includes all Monte Carlo simulations with reinforcement costs which are smaller than the first quartile boundary for the business as usual scenario (red bars). This refers to all model runs with relatively equally distributed wind power plants at the end of the business as usual scenario. In the second group all cases with reinforcement costs above the third quartile boundary for the BAU scenario are included, which refers to a more centralized wind mill distribution pattern (green bars). In Figure

31 the average welfare and welfare component development (Producer surplus, consumer surplus, spatial externalities) based on the BAU scenario is shown for both: the spatial externality avoidance strategy and the regional economic encouragement strategy. According to the illustration we observe an increasing strategy impact with increasing reinforcement costs.

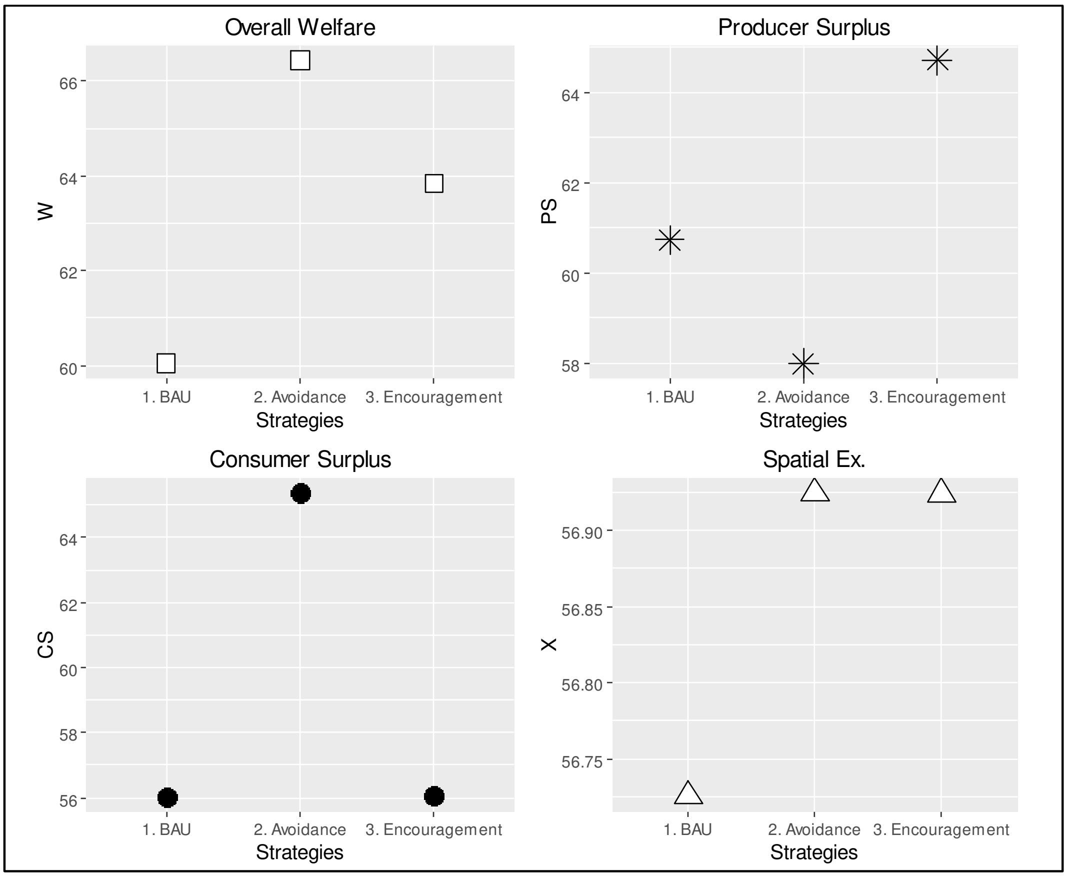


Figure 30: The average welfare equation outcomes per strategy after 1000 Monte Carlo Simulations

In the previous section the existence of coalition formation costs in form of reinforcement costs are shown by computing the welfare for all existing coalition options in a sample setting. Now we can see that the welfare impact of individual strategies increases with an increase of the coalition formation costs. Accordingly, individual strategies can improve the welfare outcome if coalition formation costs exceed a certain level. To test the robustness and consistency of the finding we run 1000 additional Monte Carlo simulations without reinforcement costs with the result that the business as usual scenario without any regional strategy outperforms the other regional strategy scenarios in terms of welfare outcome and spatial externalities avoidance.

After examining the general strategy impacts, depending on the initial distribution of the wind mills during the BAU scenario, the role of the strategy decision parameters γ and λ and the tax and subsidy level will be examined. Like in the previous policy analysis we will first look at their statistical importance for the welfare development via OLS and GAM models before we illustrate their resulting main effects as direct results of the GAM. The main effects show us the impact of chosen parameters via a scaled plot on the explanatory variable.

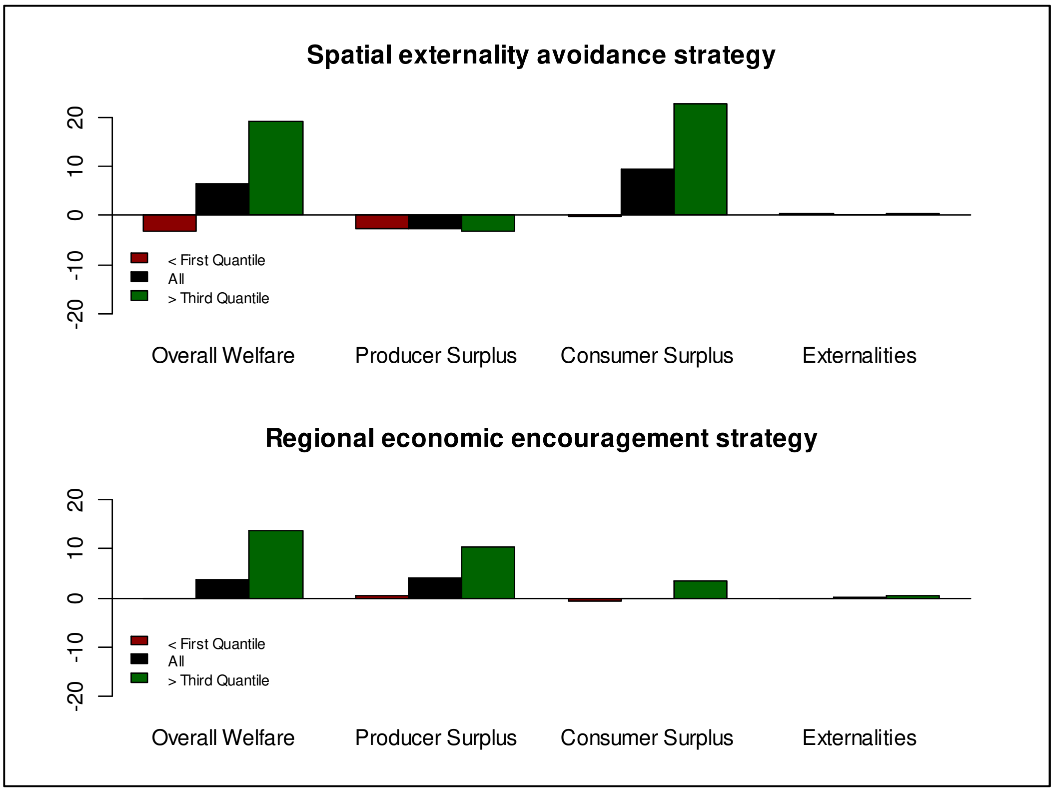


Figure 31: The welfare component development in comparison to the business as usual scenario for both strategy types in dependence of the reinforcement costs in the business as usual scenario

Both statistical models prove a high importance of the strategy decision parameter γ. Therefore, the determined boundaries for the regional economic encouragement strategy decision are crucial for the resulting overall welfare. The maximum welfare improvement is reached if γ is close to one. Accordingly, the application of the regional economic encouragement strategy is most successful if the local welfare minus the spatial externalities falls below the initial value at the beginning of the model run.

Contrary to γ the strategy decision parameter λ is only significant for the GAM. The main effects reveal that the overall efficiency strongly depends on the sensibility for spatial externalities. If the critical spatial externality level for the application of the spatial externality avoidance strategy is set too low, the overall welfare development can be negative. However, a very high sensibility for spatial externalities can lead to a complete ineffectiveness of the avoidance strategy, which would be the case if nobody was motivated to apply the mentioned strategy.

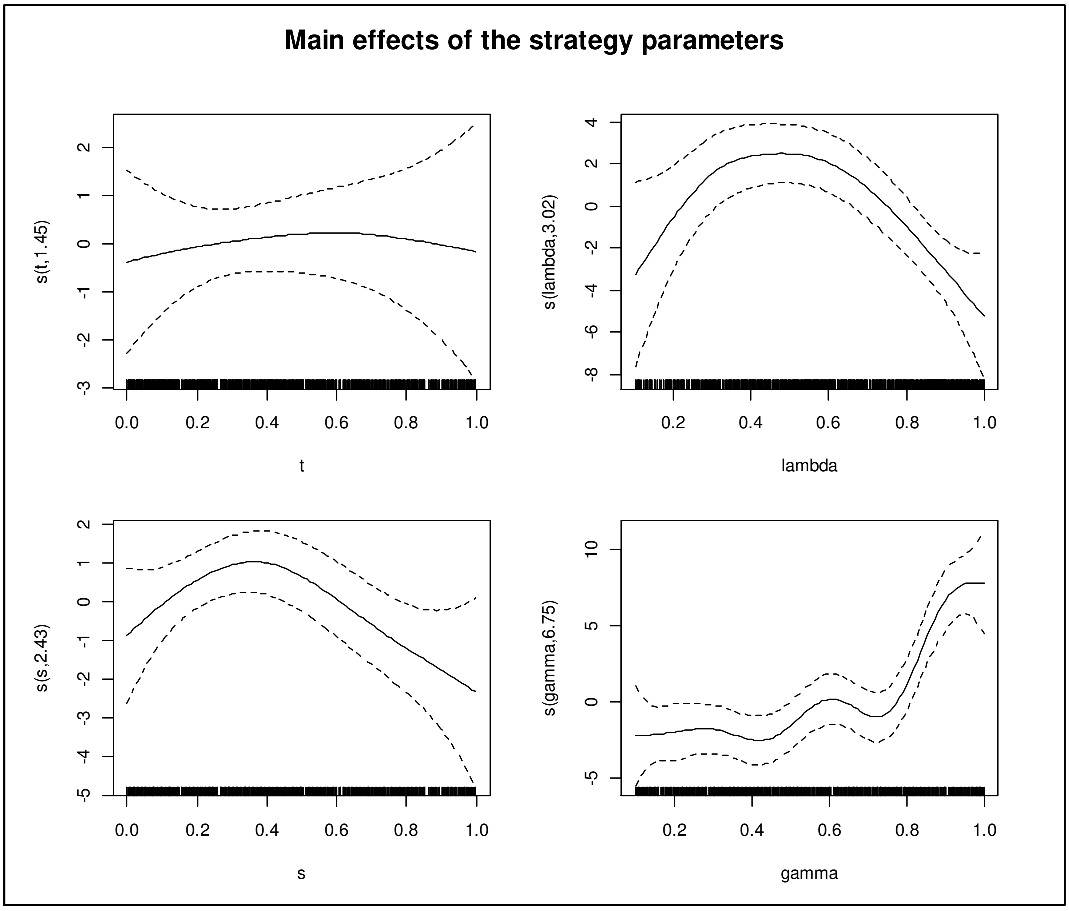


Figure 32: Resulting main effects after the application of the GAM for the tax and subsidy level and the strategy decision parameter λ and γ as explanatory variables and Δw as dependent variable

The importance of the tax level is not significant for neither of the statistical models. Nevertheless we observe a weak negative U-shape within the main effects. This is reasonable as a tax rate close to zero may not affect the site assessment of a producer. Whereas a very high tax level is comparable to the land use restriction policy. Consequently, an optimal tax rate should be in between both extreme values.

In case of an implemented subsidy, the observed negative U-shape is significant considering a GAM. The reasons for the observation are comparable with the tax level argumentation, with the difference that very high subsidy levels can lead to a negative consumer surplus, which is not plausible given the defined plausibility assumption of chapter 2. All main effects mentioned as results of the GAM calculation are illustrated in Figure 32, together with an applied smoothing function value at the y-axis as a result of the leave-one-out cross validation method.

But still the consequences on the individual level remain unclear. Therefore, we focus on the average impact on the consumer centre level in the following examinations. As we have introduced some parameter disturbances to identify potential thresholds, we have based our analysis for all welfare equation element developments on demand units to harmonise the outcomes among the model runs and consumer centres. If we compare the regionally based outcomes of both strategies with each other we notice fundamental impact differences between both strategies.

For the spatial externality avoidance strategy scenario we observe a negative development of all welfare equation elements per demand units if a regional tax has been implemented by a consumer centre. All welfare equation elements per demand unit increase if the spatial externality avoidance strategy has not been applied by a consumer centre. But the changes are significantly smaller. Therefore, we can argue that the application of the spatial externality avoidance strategy has a negative impact on consumer centres whereas the remaining consumer centre benefits from the decision out of welfare perspective.

For the regional economic encouragement strategy we observe nearly the opposite. All welfare equation elements per demand unit, except for the consumer surplus, decrease if the strategy has not been applied, and increase if the encouragement strategy has been applied. The opposite development of the consumer surplus can be explained by the guaranteed subsidise which has to be paid by the consumer centre as additional producer incentive.

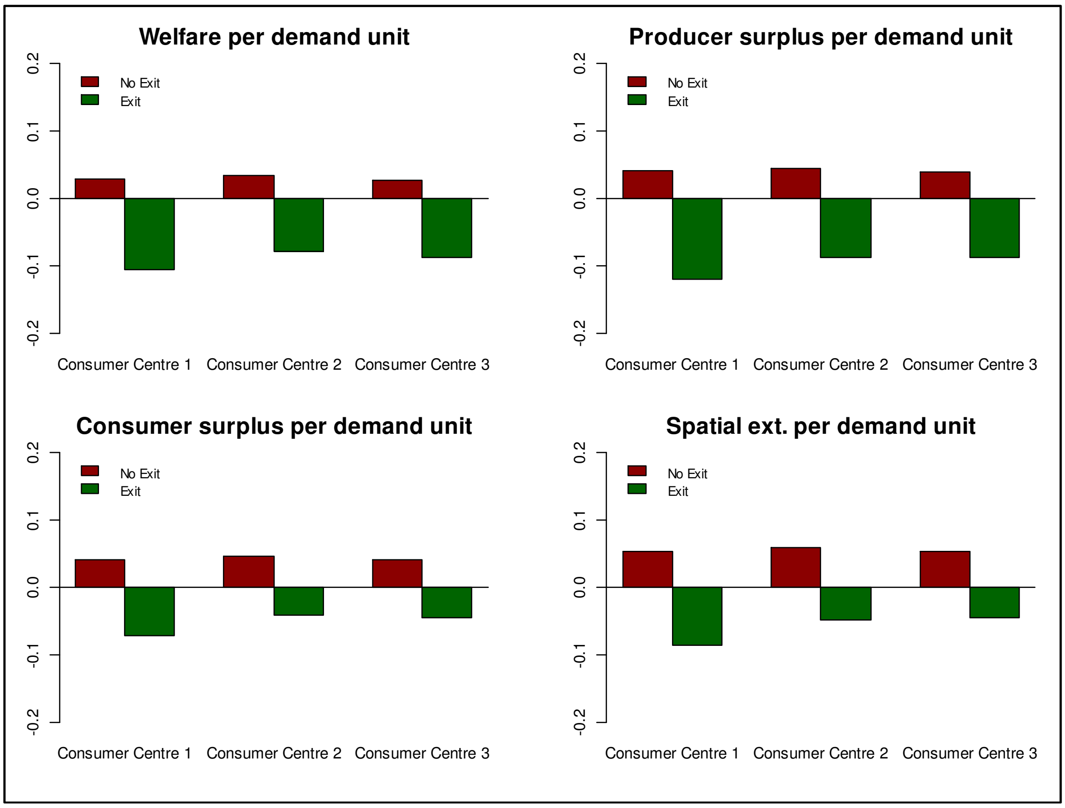


Figure 33: The average welfare component development per demand unit after the application of the spatial externality avoidance strategy.

Therefore, the application of the strategy has a strong impact on the producer surplus due to the extra payments. Because of the additional regional support the chances to achieve higher wind power deployment rates increase, which lead vice versa to a higher average spatial externality rate. Nevertheless the increase of the producer surplus seems to overcompensate the negative development of the consumer surplus and the spatial externalities. Consequently, the general welfare within the catchment area of a consumer centre increases if the regional economic encouragement strategy has been applied whereas the general welfare in the remaining catchment areas decreases.

Figure 33 and 34 summarise the consumer centre specific average welfare and welfare equation element development results per demand unit concerning the application of the spatial externality avoidance and regional economic encouragement strategy. The red bars summarise all model runs where the consumer centre did not apply the strategy and the green bars show all results where a strategy has been applied by a consumer centre.

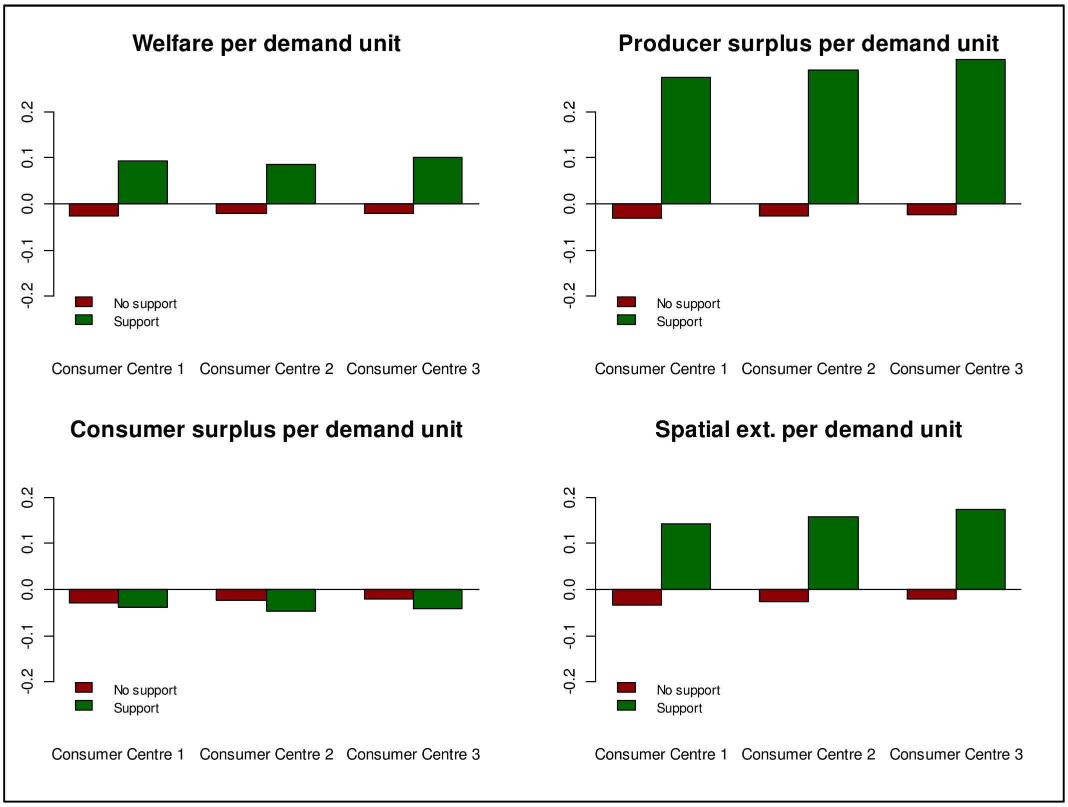


Figure 34: The average welfare component development per demand unit after the application of the regional economic encouragement strategy.

5.4.3 Strategy Impact on the regional net utility of the consumer centres

But still we cannot make a final statement about the consumer centre's perspective without an examination of the regional net utility development. This is important as an increasing or decreasing producer benefit via a changing producer surplus did not directly affect the regional benefit whereas the regional net utility takes the trade-off between increasing spatial externalities and an increasing consumer surplus into account. Figure 35 shows us that consumer centres only benefit if they apply the spatial externality avoidance strategy via an implementation of regional tax.

The application of the regional economic encouragement strategy leads on average to a decrease of the consumer centre's regional net utility. At the same time it is interesting to see that a strategy application of one particular consumer centre affects the outcome of the remaining consumer centres, but to a minor degree as the actual strategy application. Nevertheless the regional net utility is likely to decrease if a particular consumer centre starts to implement an additional regional subsidy. This is reasonable due to the fact that the spatial externality increase is bigger than the regional consumer related benefit from RES. On the contrary consumer centres are also likely to benefit if someone increases the regional support due to the application of an additional regional economic encouragement strategy.

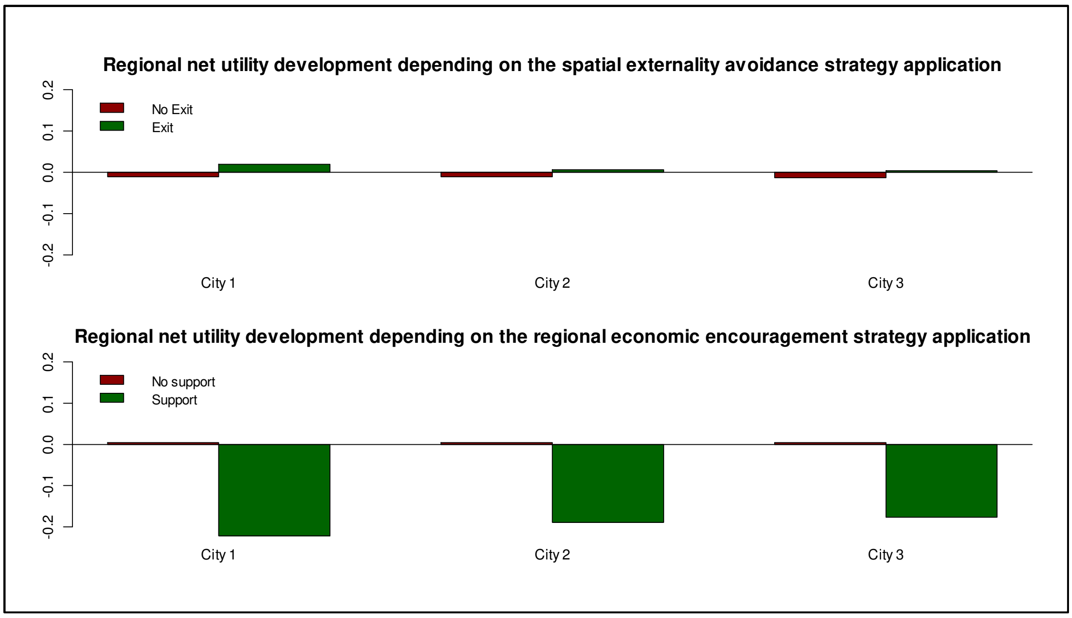
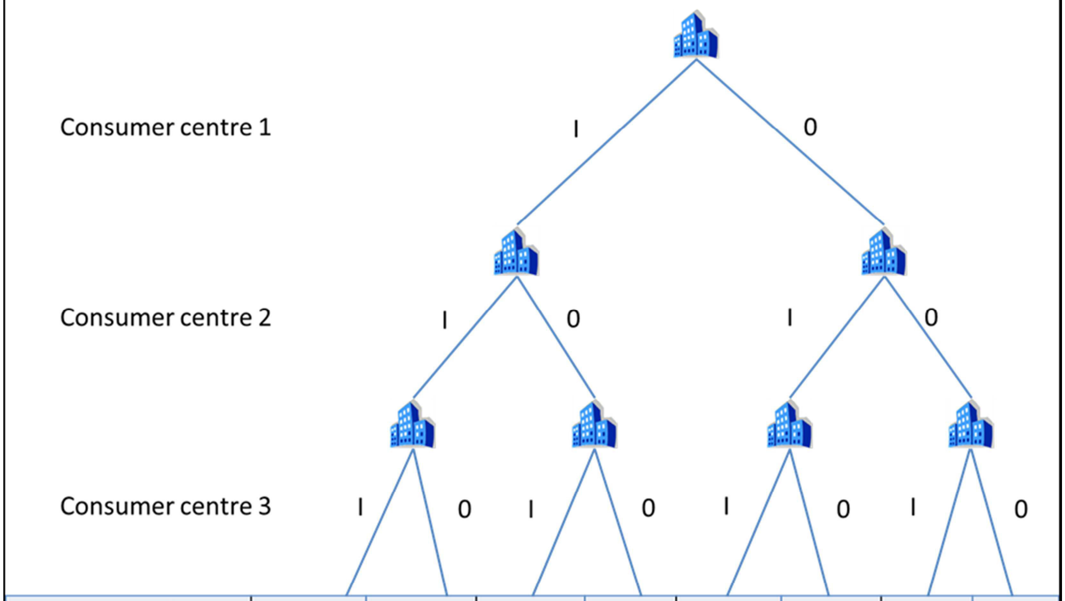


Figure 35: The regional net utility development per consumer centre and strategy option

So far we have only analysed the average outcomes for the strategies without looking at the existing strategy profiles for a single model run, whereas a strategy profile is the vector of the applied strategy per consumer centre per model run. A decision tree with all individual strategy combinations has been drawn. Afterwards the average payment development in percent has been computed for all existing strategy combinations which can be found within the sample. Both have been illustrated together in Figure 36.

Therefore, it is now possible to detect dominant strategies which are defined as strategies consumer centres would always choose considering the payoff matrix and the chosen strategy of the other participating consumer centres. If every consumer centre choses the same strategy, we can detect a Nash Equilibrium.



Avoidance Strategy	**(-8,-7,-7)**	**(0,11,-17)**	**(27,-20,0)**	**(24,-8,-8)**	**(-18,13,0)**	**(-8,16,-4)**	**(-8,-4,10)**	**(0,0,0)**
Encouragement Strategy	-	**(-76,-100,-3)**	**(-58,4,-58)**	**(-225,5,5)**	**(15,-73,-69)**	**(12,-440,5)**	**(4,9,-383)**	**(0,0,0)**

I...Strategy applied 0....Strategy not applied

Figure 36: The strategy decision tree plus the payment development matrixes per strategy combination

In the case of the spatial externality avoidance strategy we cannot detect a dominant strategy for the consumer centres. Despite observing an increase of the consumer centre´s regional net utility while applying the spatial externality avoidance strategy for most of the consumer centre strategy combinations, a negative payoff development is illustrated if every consumer centre applies the spatial externality avoidance strategy. Therefore, no Nash Equilibrium can be observed. This is reasonable as the additional tax implementation by all consumer centres does not affect the spatial allocation of the producer.

For the regional economic encouragement strategy we observe a dominant strategy. Now the BAU strategy dominates the application of the regional economic encouragement strategy. Accordingly, every consumer centre would consider not to not apply the encouragement strategy. Consequently the BAU strategy for all consumer centres is the resulting Nash Equilibrium where no changes in the consumer centre payments will be observed. Furthermore, the results reveal that the regional economic encouragement strategy application has in average a very strong negative consequence regarding the regional net utility development with changing rates in the mid three-digit percent range.

5.4.4 Impact of the strategy choice on the fairness criteria

For the assessment of the strategy impact on the fairness we calculate the resulting mean value of the *Gini* coefficient. The results differ from -10% for the spatial externality avoidance strategy to +10% for the regional economic encouragement strategy. Therefore, only the spatial externality avoidance strategy can improve the overall fairness, as the Gini coefficient can be between 0 and 1, whereas 1 means that one player or person has everything and zero stands for a completely equal welfare distribution among the participating players or consumer centres.

After examining the average Gini coefficient per scenario, the role of the strategy decision parameters γ and λ and the tax and subsidy level will be examined again. Like in the previous policy analysis we applied an OLS and GAM to measure the importance of the strategy parameters on the *Gini* development. Afterwards the GAM main effects have been illustrated in Figure 37.

Both statistical models reveal the importance of all strategy parameter for the development of the Gini coefficient. All mentioned parameters have a significant impact on the fairness. Consequently, the negative fairness impact of the regional economic encouragement strategy increases with an increase of the subsidy level and the strategy decision parameter γ. Again we discover the opposite dependence for the spatial externality avoidance strategy. Accordingly, the fairness increases if the tax level increases as well. For the strategy decision parameter λ we find a local minimum close 0.3. Therefore, it seems to exist an optimal spatial externality avoidance strategy application level which leads to the best fairness results.

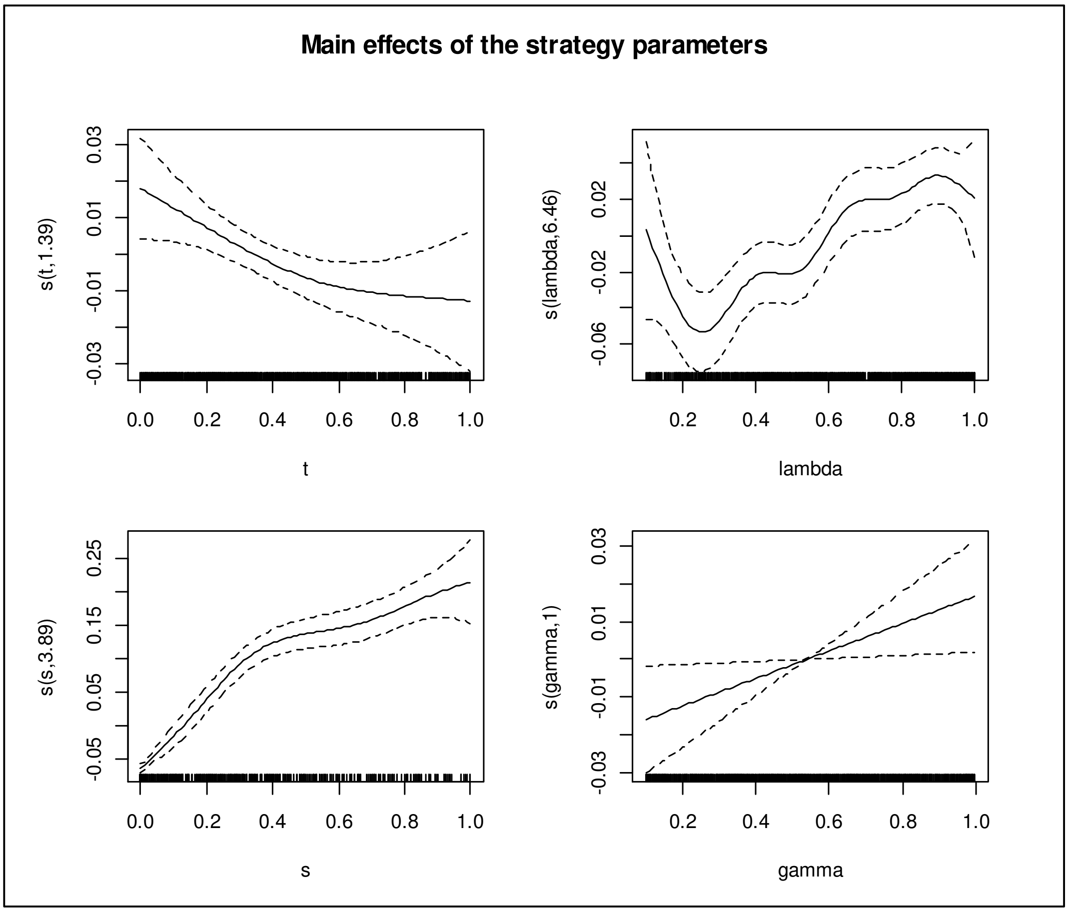


Figure 37: Resulting main effects after the application of the GAM for the tax and subsidy level and the strategy decision parameter λ and γ as explanatory variables and Δw as dependent variable

5.5 Summary and conclusion

Within this chapter 5 the initially defined grand coalition assumption of the consumer centres has been softened in order to evaluate the efficiency and fairness impact of regionally specific behaviour. Two different approaches have been chosen to provide a broader perspective on self-sufficient strategies of the consumer centres. In a first step the basic assumption of a lead out grand coalition has been tested, therefore, the grand coalition always leads to the most efficient outcome. A Monte Carlo Simulation with 1000 model runs including the complete coalition structure of a three agent model has been carried out. The results have revealed a violation of the superadditvity assumption of the ABM if distribution costs in form of grid reinforcement costs arise. These costs can be defined as coalition formation costs. Consequently, the cooperative game theoretical approach has been rejected in favour of a heuristic approach which takes regional specific strategies into account.

A spatial externality avoidance and a regional economic encouragement strategy have been implemented with the help of simple heuristic rules. An avoidance strategy will be applied if a region is not willing to accept similar RES deployment rates like in the past due to increasing regional spatial externalities with the consequence that an additional tax will be introduced in order to slow down the regional RES deployment. The encouragement strategy on the other hands has the aim to increase the regionally specific benefits of RES. Accordingly, additional regional subsidies will be implemented in order to attract a bigger RES capacity. These strategies have been tested again with 1000 Monte Carlo Simulations with the result that regional strategies do have a positive welfare effect in average which increases if the former coalition formation costs in form of grid reinforcement costs are high. However, the improvement strongly depends on the application sensitivity which significantly differs between both strategy types. The regional net utility impact strongly depends on the reaction of the remaining consumer centres.

Chapter 6

Case study: A scenario based analysis inspired by Germany

6 *Case study: A scenario based analysis inspired by Germany*

6.1 Overview

So far we have analysed either the impact of particular regulation based and marked based policies on the efficiency and fairness outcome of the entire landscape (chapter 4), or we have focussed on the impact of certain region specific strategies on similar outcome parameters plus adding a regional perspective by considering additional variables, like the regional welfare or the regional net utility (chapter 5). But in a complex transformation process, like the transition from a conventional electricity production to renewable energy sources, all elements interact with each other. Accordingly, it is not enough to use an isolated perspective on decisive efficiency and fairness impacts. However, it is not possible within the created ABM framework to evaluate all possible interactions. Therefore, we focus on a conceptual case study, which is inspired by German landscape and policy properties in this chapter 6.

Consequently, the regional basic parameters have been altered to represent three German regions (North, South West and South East) for the final strategy and policy analysis. We work with stylised facts for the consumer centres and their corresponding catchment areas without considering precise statistical data of strictly defined regional representations for all parameters. Furthermore, a *policy mix* has been implemented which reflects the German policy conditions. Accordingly, the initial scenario differs from the previous strategy analysis, where the *Market I* scenario has been applied as *BAU* scenario.

For the construction of the regional specific stylised facts, aggregated federal state data has been used. The northern region has been represented by the federal states of Schleswig-Holstein, Mecklenburg-Western Pomerania, Lower Saxony and the city states of Hamburg and Bremen. South west specific facts are based on the aggregated federal states' data of Baden-Württemberg, Hesse and Rhineland-Palatinate. The south east is based on the federal state data of

Bavaria. As only three regions that should somehow differ regarding their regional properties can be represented, not all German federal states have been considered for the construction of the regional specific stylised facts.

The objective of the analysis is to show the interaction between strategic regional behaviour of the consumer centres and the application of policies against the background of regional differences. Therefore, the presented tools of the previous chapters have been used. Accordingly, 1000 Monte-Carlo Simulations have been executed considering the regional specific of the defined areas. This time the spatial externality avoidance and regional economic encouragement strategy have been applied under the *Market I* and a defined *Policy Mix* which consists of regulation and market based policies inspired by the German case study. Consequently, every Monte-Carlos Simulation consists of six scenarios with a different strategy and policy setting.

6.2 Model specification

6.2.1 The parameter modification

In a first step we altered the energy consumption level of the three consumer centres. Therefore, we evaluated the gross electricity consumption of the year 2012 for all assigned federal states. The data has been made available by the renewable energies agency in Germany and is based on the information of all relevant state statistical offices. Considering the data a significant difference between the South West with 143,559 TWh and the North with 98,882 TWh together with the South West with 92,787 TWh can be identified. Consequently, we reduce the electricity demand by 15% based on the basic parameter set of chapter 2 for the consumer centres which represent the North and the South West. At the same time the electricity demand of the consumer centre, representing the South East, will be increased by 30% for the scenario based analysis.

For the construction of regional specific stylised facts regarding the multiplier effect, which is defined as regional economic welfare effect because of the RES installation that for example emerges through tax revenues and maintenance companies (Hirschl et al. 2011; Kosfeld 2011), we cannot rely on a specific dataset due to the complexity of the concept. RES employment data, provided by the GWS (Ulrich and Lehr 2013), which takes all employees related to the direct production process, the maintenance and operation of RES into account, are for example strongly correlated with the actually installed capacities within the federal states in the case of wind power. But RES employees do not include all regional value adding aspects. Company profits and local tax revenues are neglected. Another important element is the locally added value due to the production of specific plant components for RES. Lehr et al. (2015) mention in their study about the employment due to RES in Germany that 45.3% of the advanced service for wind onshore plants are carried out within Germany itself. Accordingly, regions with a good supplier industry have a higher regional advantage than regions without such an industry. As the typical mechanical engineering hotspots can be found in the south of Germany and particularly in Baden-Württemberg, the multiplier parameter of the South West and the South East will be set higher in comparison to the multiplier value of the North.

Besides the regional adaption of economic parameter also landscape specific parameter will be altered. Therefore, we use the average wind condition data on a hub height of 80 meters that has been collected by the German weather service between 1981 and 2001 (DWD 2014) to calculate regional specific value regarding the average physical endowment of the consumer centres’ catchment areas. Considering the data the North has the highest average wind conditions of 5.95 m/s, the South West shows with 5.32 m/s the second highest value and the South East reaches with 5.11 m/s the lowest average wind conditions. Consequently the energetic potential parameter of the North will be set 10% above average whereas the same parameter will be set 10% below the South West average.

For the evaluation of the spatial externalities we use the hermeroby index which is provided by the Leibnitz Institute of Ecological Urban and Regional Development (IOER 2015). The index is explained in the following way by the IOER:

> "The term hemeroby is derived from the Greek hémeros (tamed, cultivated) and bios (life). Hemeroby describes the totality of anthropogenic interventions in the natural environment and can be seen as a reverse measure of naturalness, if these interventions are reversible. The following seven levels of hemeroby are used to classifiy forms of land use or land cover. Level 1 is used for landscapes with no cultural influence which can be defined as ahemerob. On the contrary Level 7 is used for methahemerob landscapes with extreme cultural influence which lead to a destruction of ecosystems. This indicator provides a general statement on the quality of land consumption by anthropogenic intervention."

The general differences between all defined regions are quite small. However, significant differences can be found between the South East, the South West and the North. The North shows the highest value with 4.33. Therefore, we can observe more anthropogenic interventions in comparison to the South East where we get an index value of 4.04. A relatively low anthropogenic intervention rate can be observed in the South West with 3.91.

Region	Consumer Centre	Energy Consumption level	Multiplier Effect	Average Energetic Potential	Average Spatial Externalities
North	Consumer Centre 1	Low - 15%	Low - 50%	High + 10%	Low - 5%
South West	Consumer Centre 2	High + 30%	High + 50%	Medium +/- 0%	High + 5%
South East	Consumer Centre 3	Low - 15%	Medium +/- 0%	Low - 10%	Medium +/ 0%

Table 7: The regional specific parameter modification per consumer centre depending on the regional stylised facts

With all information at hand the regional specific parameters have been modified per consumer centre or stylised region in such a way that the consumer centre variation matches the observed data. The starting point for the variation is the basic parameter set of chapter 2. Table 7 summarizes all regional specific parameter variations for the concerning consumer centre or stylised region. As the regional specific variation is normally distributed the average values of all altered parameter of the computed sample are not significantly different from the sample of the previous section 6.4.

6.2.2 The applied policy scenario combination

RES and especially wind power face many land-use related restrictions coming from different legislations. Beside the Federal Pollution Control Act (BImSchG 2014), which determines the minimal distance between settlements and emission sources, also the German Federal act for the protection of Nature (BNatSchG 2013) shortens the space supply for RES. Accordingly, only 50% of the virtual landscape area are available for wind mill constructions due to land-use restrictions which restrict cells with the highest spatial related externalities.

The integrated support scheme for RES producers of the Market I scenario will be supplemented with an additional reference yield model (Market II). Therefore, the reference yield model boundaries and the slope of the remuneration line, determined by the factor ψ, have been calibrated based on the German Energy Source Act (EEG 2014; Neddermann 2014). As the actual German RES policy does provide neither a nodal nor a zonal pricing scheme, all arising reinforcement costs have to be bearded by the consumers.

6.3 The impact of the Policy Mix on the efficiency and fairness

In a first step the produced Monte-Carlos Simulation sample has been evaluated regarding the policy mix impact on the efficiency. So far all policies have been analysed separately, without considering the interactions between them. Now a regulation-based policy and an additional market-based policy will be applied at the same time in order to estimate occurring side effects.

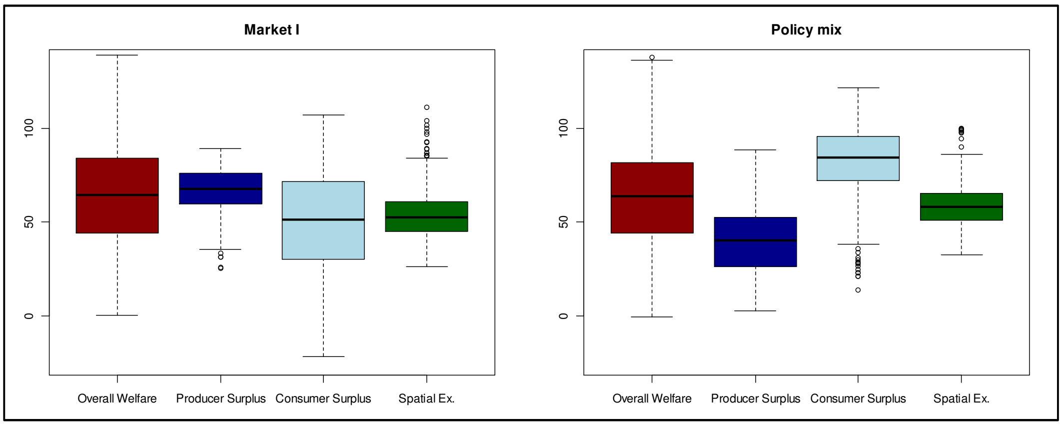


Figure 38: Boxplot of welfare equation elements of the Market I and the Policy Mix scenario

Therefore, the welfare equation outcome distribution of the model sample will be shown in form of several boxplots in Figure 38, where the *Market I* scenario will be compared to the *Policy Mix* scenario. For the *Policy Mix* scenario a significant producer surplus decrease combined with and increasing consumer surplus, can be observed. These changes can be explained with the policy applications which are in favour of the consumer site. The included reference yield model within the RES support schemes reduces for example windfall profits of producers due to the remuneration reduction at sites with very good wind conditions.

Furthermore, the reinforcement costs can be reduced because of the applied land-use regulation policy, which leads to a more evenly distribution of the wind power production plants in comparison to the *Market I* scenario. But despite the application of a regulation-based policy which tends to reduce spatial externalities, a significant increase of spatial externalities can be observed for the *Policy Mix* scenario sample. That can be in part explained by the average power plant efficiency decrease due to the implementation of the reference yield mechanism. Accordingly, more plants have to be built with the consequence that the average spatial externalities increase. This effect has been already observed in a separated evaluation of the *Market II* scenario without any land-use regulations.

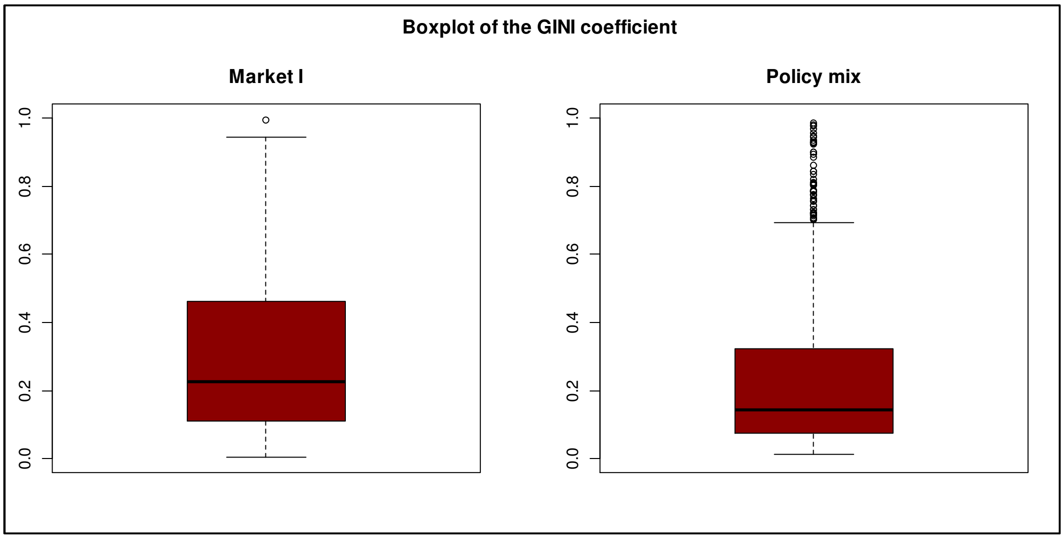


Figure 39: Boxplot of welfare equation elements of the Market I and the Policy Mix scenario

In average no significant welfare improvement due to the application of the *Policy Mix* can be detected. It rather exists a trade-off between a consumer surplus increase and a producer surplus decrease. But the evaluation of the average computed fairness via a GINI coefficient reveals that the implemented *Policy Mix* leads to a significant fairness improvement, which means that existing regional differences can be better compensated.

6.4 Strategy impact on the welfare components

Within the next analysis step the impact of the defined spatial externality avoidance and regional economic encouragement strategy from section 5.3 will be evaluated for the *Market I* and the *Policy Mix* scenarios. Like for the previous model sample analysis we compare the welfare equation mean values of all 1000 model runs with each other to determine the average effect of the strategies. Therefore, the average welfare equation outcomes for every strategy-policy combination numbered consecutively from 1 to 6 are illustrated in Figure 40. A diametrical difference of the strategy impact regarding the two applied policies can be determined. The initial positive strategy welfare impact, which can be observed for the *Market I* scenario, turns into the opposite for the *Policy Mix* scenario.

In the case of the *Market I* scenario the results are almost identical with the findings of the previous section 5.4.1 illustrated in Figure 30, except of small variations regarding the producer surplus and the consumer surplus, which increased (producer surplus) and decreased (consumer surplus) by 10%. These differences can mainly be explained by regional specific wind condition alterations. Accordingly the wind power plant concentration in the northern regions rises with the consequence of higher producer profit shares and higher reinforcement costs.

Nevertheless, the spatial externality avoidance and the regional economic encouragement strategy implication impacts remain the same. Consequently, both strategies can increase the average overall welfare within a *Market I* policy setting. To understand the occurring negative strategy impact for the *Policy Mix* scenario with low initial reinforcement costs, the consumer surplus differences between both policy-scenarios without any regional strategies (BAU) have to be examined. A significant difference between both policy scenarios can be revealed by comparing the reinforcement costs. The *Policy Mix* tends to produce more decentralised RES production patterns, which decrease the average reinforcement costs by a third with the result that the average consumer surplus decreases and the possibility for more efficient allocation patterns shrink as well. Therefore, the strategy impact on the consumer surplus is only positive if the reinforcement costs have been very high for any initial Policy Mix scenario without any regional strategies (BAU-Mix).

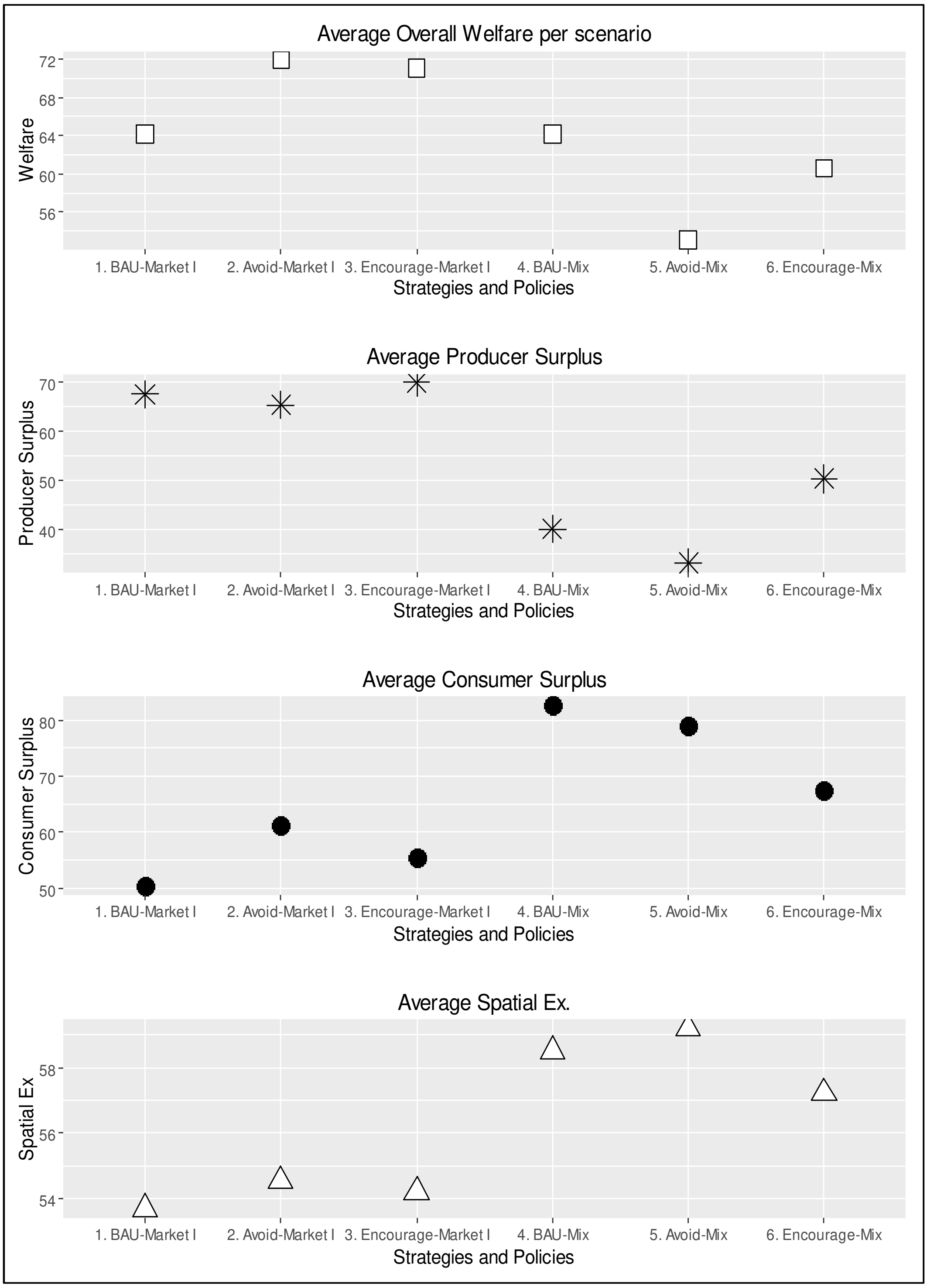


Figure 40: The average welfare equation outcomes per applied strategy and policy

Again the results indicate a high importance of the reinforcement costs due to their high impact on the consumer surplus development. To evaluate their importance in more detail the sample will be split again in two additional subsamples. The first subsample contains all model runs with low reinforcement costs within the BAU scenario for each policy. Accordingly, the reinforcement costs of all model runs within the first group are below the first quartile value of the complete sample (red bars). For the second group all model runs with high reinforcement costs (above the third quartile of the complete sample) within the BAU will be selected (green bars).

In comparison to the previous reinforcement cost based analysis of section 5.4.1, illustrated in Figure 31, the observed absolute changes of the *Market I* policy do not show any significant differences. Again the positive strategy increases with higher initial reinforcement costs due to the reason of a higher wind power plant decentralisation degree. Even for the *Policy-Mix* scenario the similar relationship between reinforcement costs and the welfare impact can be observed with the difference that we see a general welfare decrease which gets smaller with high initial reinforcement costs. In the following only the results for the *Policy-Mix* scenarios will be illustrated as they show significant differences to the previous analysis of chapter 5.4.

In the case of the spatial externality avoidance strategy the welfare reinforcement cost dynamic can be explained by the consumer surplus variations, whereas only minor changes can be observed for the producer surplus. But in comparison to the observation of section 5.4.1, the spatial externality avoidance strategy does only have a positive consumer surplus impact if the initial reinforcement costs have been very high for the business as usual scenario because this kind of costs have already been significantly reduced by the implementation of the *Policy Mix*. Therefore, the spatial externality avoidance strategy can even lead to grid specific efficiency reductions which negatively affect the consumer surplus. For the regional economic encouragement strategy the producer surplus increases and raises even more with higher initial reinforcement costs. That can be explained by a higher subsidy possibility share if reinforcement costs increase, as the application is initialised by a defined regional welfare boundary value which does not take any spatial externalities into account.

Only for the subsample with very high reinforcement costs (green bar) we observe a significant welfare increase due to the small consumer surplus reductions. Accordingly, the regional economic encouragement strategy can reduce the grid reinforcement costs but leads at the same time to a wealth redistribution between the RES producer and the consumer of electricity. Figure 41 once again illustrates the high initial importance of reinforcement costs for the absolute welfare equation elements' impact.

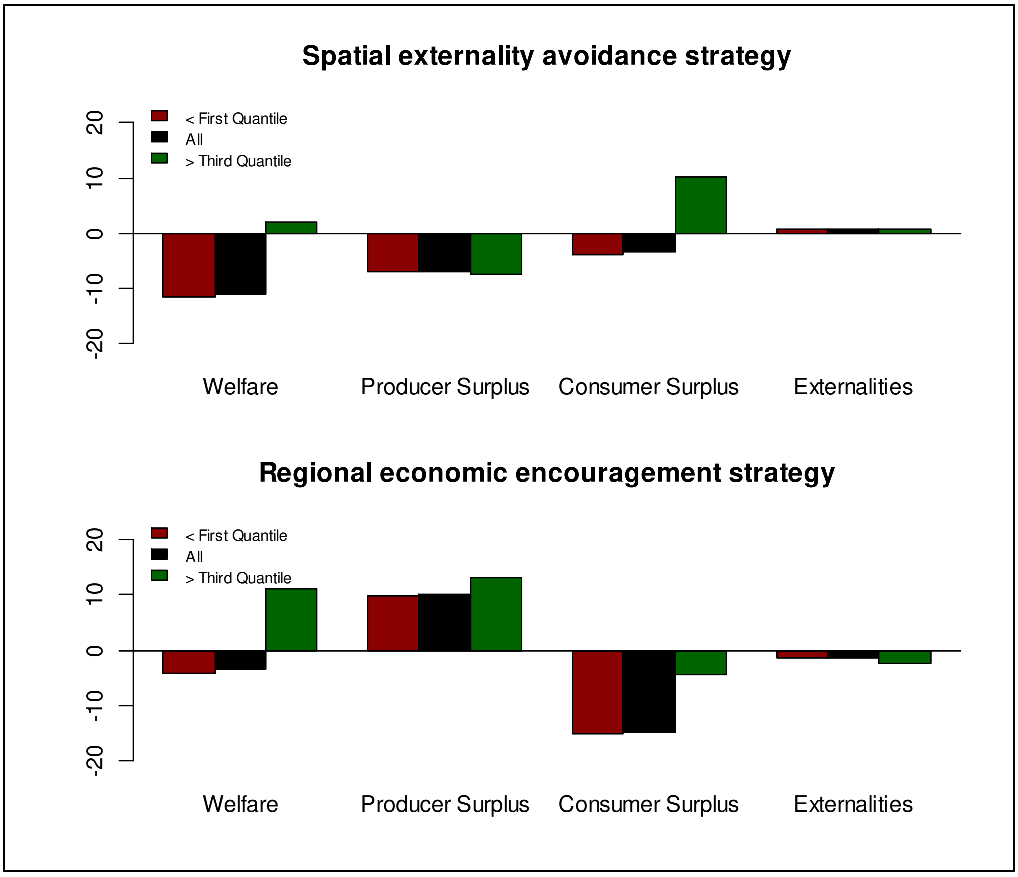


Figure 41: The welfare component development in comparison to the business as usual scenario for both strategy types for the Policy-Mix scenario in dependence of the reinforcement costs in the business as usual scenario.

Also the impact of the strategy decision parameters γ and λ together with the tax and the subside level have been examined with the help of an OLS and GAM model. The resulting main effects of the strategy decision parameter for the policy scenario *Market I* are once again almost identical with the first sample analysis of the previous chapter 5.4.1. Accordingly, γ and λ have a significant impact on the efficiency of the model regarding both statistical models. Again the observed GAM main effect maximum welfare improvement for λ is between 0.3 and 0.4 and the main effect curve for γ steadily increases. But this time a significant tax t and subsidy s level efficiency impact can be identified in both statistical models. Therefore, the regional strategy design matters in term of efficiency if the landscape is determined by an unequal resource allocation. For both strategies an additional tax or subsidy level of 20 % of the initially guaranteed feed-tariff seems to be most promising to increase the overall efficiency.

The main effects of the *Policy Mix* scenario, illustrated in Figure 42, reveal different patterns in comparison to the previous section. For the regional spatial externality avoidance strategy we can argue that the parameter's main effects reverse. Considering the average negative efficiency impact of the strategy for the *Policy Mix* scenario, it is plausible that a higher strategy application parameter has a positive influence on the efficiency development as the barrier for the spatial externality avoidance strategy application gets bigger. Also the main effect of the tax-level parameter completely reverses. Therefore, some can argue that the highest spatially relevant signalling can be obtained by a regional specific tax between 20% and 40% of the initial feed-in tariff.

In case of the regional economic encouragement strategy application for the *Policy Mix* scenario the subside-level parameter as well as the strategy decision parameter γ have a significant impact on the efficiency development, but in comparison to spatial externality avoidance strategy findings the main effects are less clear to interpret. Nevertheless one can argue that a higher strategy application likelihood connected with a high subsidy level can avoid a negative efficiency effect.

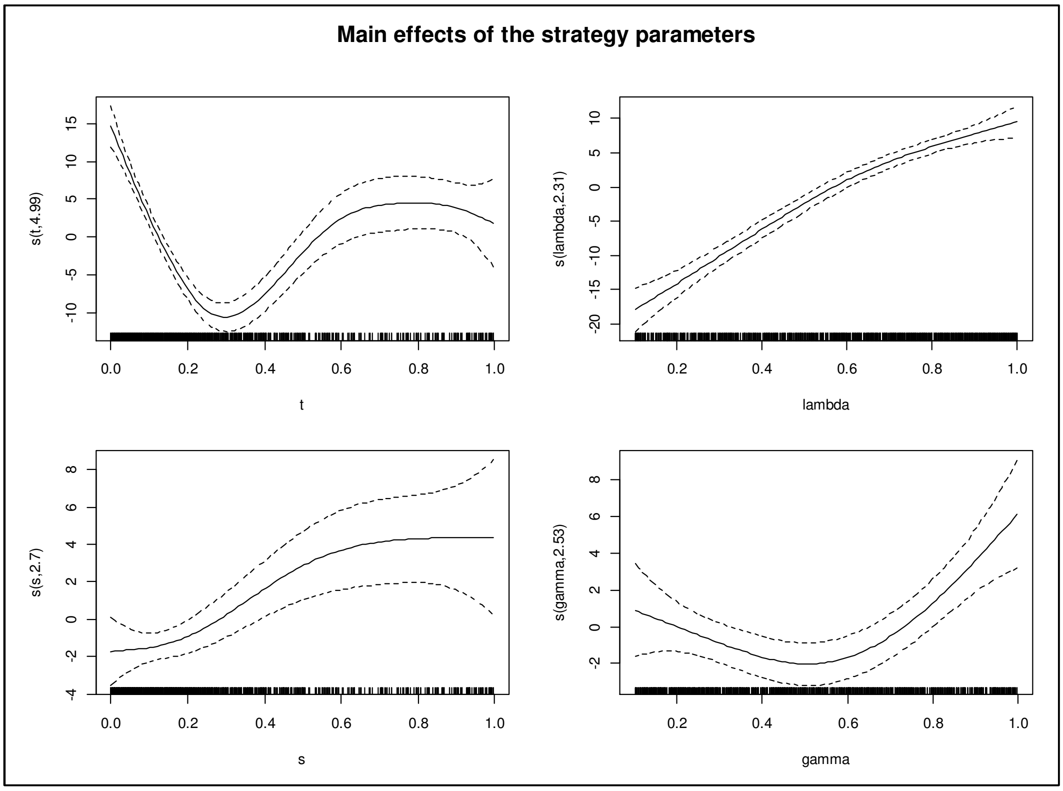


Figure 42: Main effects results of GAM with the tax level t, the subsidy level s, the strategy decision parameters λ and γ as explanatory variables and Δw as dependent variable for the Policy Mix scenario.

For the next evaluation step we measured the average region-specific changes which occur while applying or not applying a strategy. Therefore, we focus on the average absolute rate of change of the welfare and the welfare components (Producer Surplus, Consumer Surplus and Spatial Externalities). By examining the results of the spatial externality avoidance and the regional economic encouragement strategy we notice that the average regional specific effect significantly varies with the consequence that some welfare components for a specific region always increases or decreases independently from the strategic decisions of the region. Of course that depends on the altered regional specifications, which do not only affect initial spatial allocation patterns, but also the sequence of the strategy application by a homogenous decision application assumption. But these regional specifics will be weakened by the application of the *Policy Mix* consisting of regulation based and additional market based measurements.

The following Figures 43 and 44 illustrate the regional specific welfare and welfare components development of the spatial externality avoidance and regional economic encouragement strategy application for the *Policy Mix* scenario. Regarding the welfare development of the spatial externality avoidance strategy we note significant difference in comparison to the previous analysis with a homogenous setting. In general, the implementation of an additional regional tax reduces the regional specific welfare, whereas the retention strategy has a positive welfare effect. While the Northern region and the South East show similar patterns regarding the welfare equation elements the South West behaves differently.

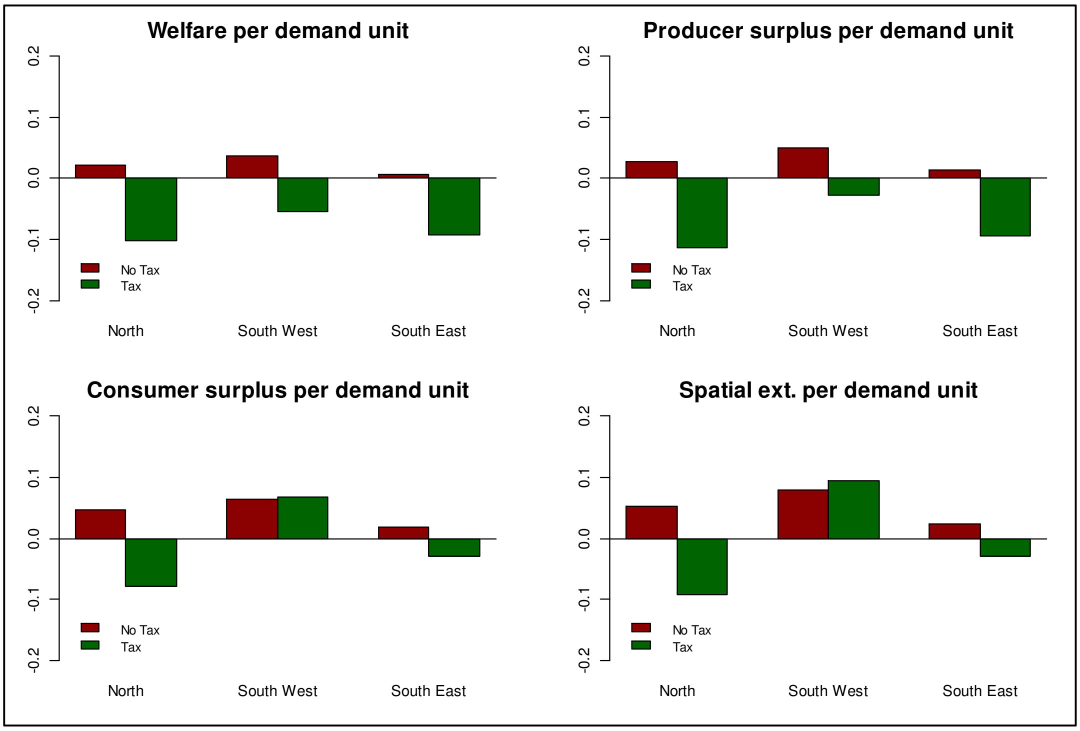


Figure 43: The average development of the welfare equation element per demand unit after the application of the spatial externality avoidance strategy.

Therefore, the consumer surplus and the spatial externalities of the South West always increase in comparison to the business-as-usual (BAU) case (where no regional strategies will be applied by any region) regardless if the South West applies the spatial externality avoidance strategy or not. A possible explanation of such an observation is the strategy application sequence of the regions. Accordingly, it is very likely that the North reaches the exit criteria first, due to its favourable wind conditions. This has the consequence that the producers tend to choose the next-best alternatives which are located in the South West. Then the wind power capacity within the region will be increased, with the consequence that the consumer surplus and the spatial externalities increase till the spatial externality avoidance strategy application condition will be reached by the South West.

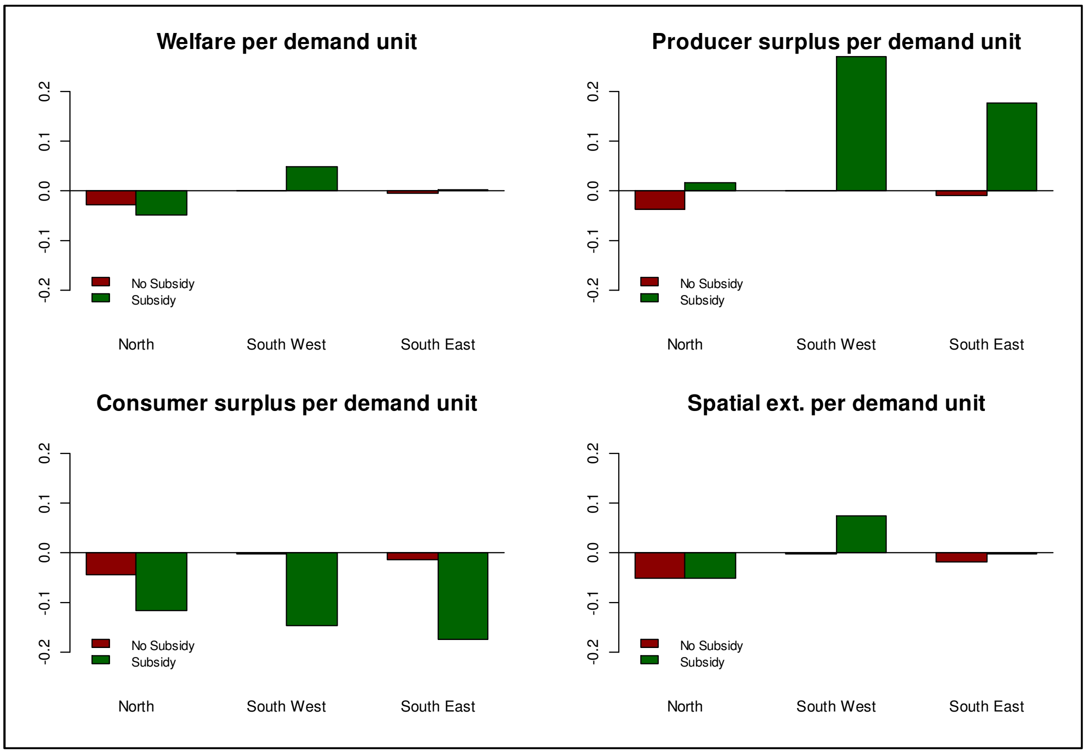


Figure 44: The average development of the welfare equation element per demand unit after the application of the spatial externality avoidance strategy.

Also in the case of the regional economic encouragement strategy application we observe differences in comparison to the homogenous setting of chapter 4.5.1. This time the region South West can increase its regional welfare if the regional economic encouragement strategy condition will be reached with the consequence of the implementation of an additional regional subsidy. Consequently, a certain surplus degree will be reallocated between the producers and consumers of the region. Furthermore, the subsidy implementation increases the spatial externalities within the South West region, but the producer’s benefits overcompensate the negative impact on the spatial externalities and the consumer surplus. For the remaining regions such a policy has a limited negative or absolutely no welfare effect.

6.5 Strategy impact on the regional net utility of the consumer centres

Before the fairness impact will be evaluated we will have a closer look at the development of the regional net utility per consumer centre to estimate the strategy impact in terms of a regional context by taking the trade-off between increasing spatial externalities and an increasing consumer surplus into account. As the applied *Policy Mix* already has an important compensatory effect on the regional net utility we do not observe clear differences for all regions. Nevertheless the probability to benefit from the implementation of regional strategies is bigger in the case of the Northern region in comparison to the South Western region, whereas the South East shows similar results like in the previous regional analysis of section 5.4.2. The outcomes are illustrated in Figure 45.

After examining the strategy depending regional net utility developments of the *Market I* scenarios that features similar results like in the illustration of the Figure 45, we can argue that these variations can be mainly explained by the regional specific differences concerning the physical endowment and economic conditions. Accordingly, the implementation of an additional regional tax would only be beneficial for the Northern region. For the remaining regions, that strategy has no impact at all, or turns out to be counterproductive. The application of the regional economic encouragement strategy is for all regions harmful, whereas the consequences for the North do not seem to be as drastic as they are for the other regions, but still they are much bigger in comparison to the spatial externality avoidance strategy, as it comes to a significant wealth re-allocation between consumers and producers inside the affected region.

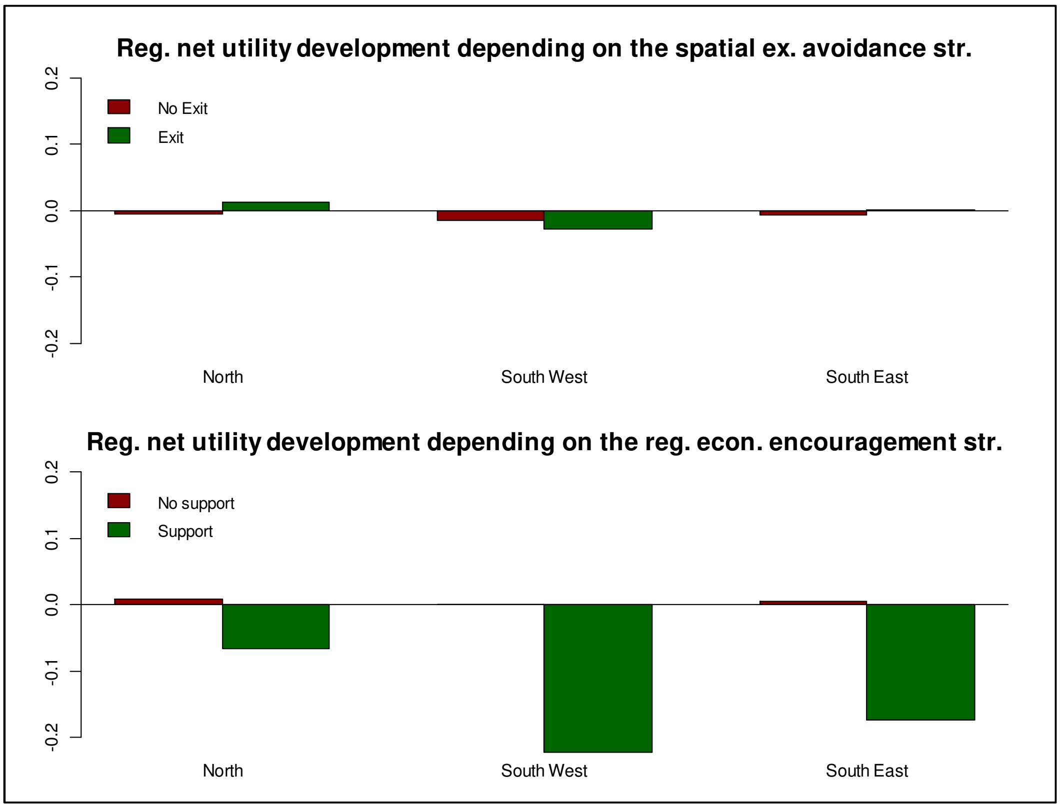
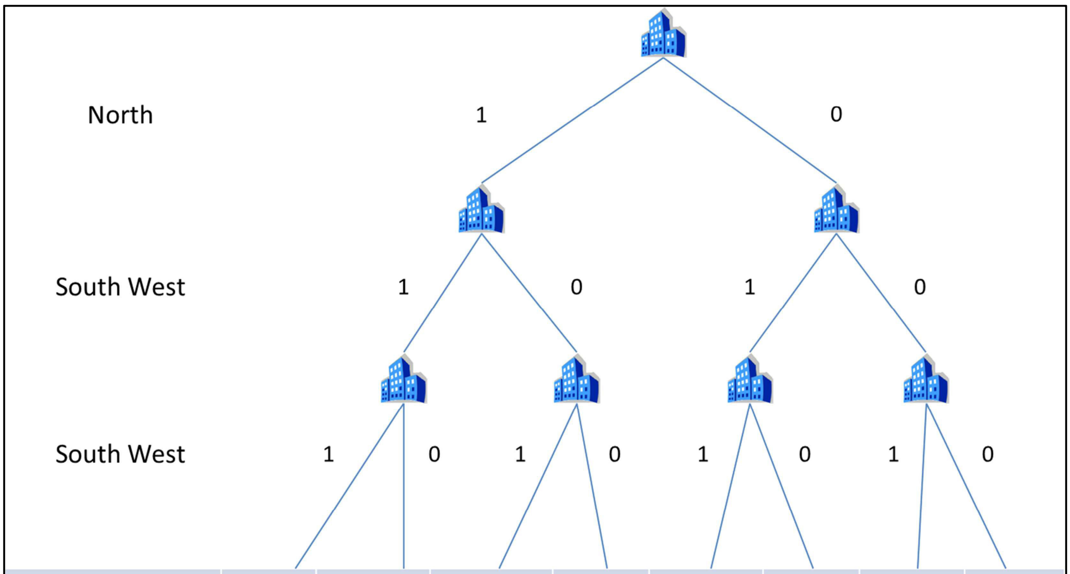


Figure 45: The regional net utility development per region and strategy option for the Policy Mix scenarios

In order to determine dominant regional specific strategies, a decision tree with all regional strategy combinations has been drawn. Afterwards the average percentage rates of change have been computed for the spatial externality avoidance and the regional economic encouragement strategy. Like in the previous analysis in section 5.4.2 we do not observe a dominant strategy in the case of a tax implementation. Therefore, the outcome strongly depends on the decision of the other regions. Consequently, the application of the spatial externality avoidance strategy bears a certain risk of a shrinking regional net utility for the particular region. Also in case of the regional economic encouragement strategy no dominant strategy can be detected for the regions. Accordingly, it applies the same for the introduction of a regional subsidy, like for the introduction of a regional tax, that the application bears a high risk of a shrinking regional net utility dependent on the strategy decision of the remaining regions.



Avoidance Strategy	(-23,29,87)	(12,-365,-26)	(13,-69,-22)	(11,-5,-38)	(-24,-13,28)	(0,-1,-1)	(3,-41,13)	(0,0,0)
Encouragement Strategy	(18,27,-66)	(-37,-57,81)	(134,119,-236)	(-82,4,11)	(31,-100,-78)	(0,4,-11)	(65,99,-143)	(0,0,0)

1 = Strategy applied … 0 = Strategy not applied

Figure 46: The strategy decision tree plus the payment development matrixes per strategy combination

6.6 Impact of the strategy choice on the fairness criteria

Finally the strategy application impact on the fairness will be evaluated. Therefore, we calculated the resulting average *Gini* coefficient of all policy-strategy combination in a first step. For the *Market I* policy scenarios we observed a general decrease of the coefficient if the regional specific strategies were applied. Consequently, the equality, defined as fairness, has been increased. While having the defined Policy Mix implemented the strategy application has the opposed effect, with the consequence that the average Gini coefficient for the regional economic encouragement strategy cases is even above the Gini coefficient of the Market I scenario without any regional strategy applications.

Once more we apply statistical models in order to determine the influence of the strategy parameter on the Fairness variable. Again all parameters have shown a significant impact on the *Gini* coefficient, whereas the subside-level parameter *s* has had once more the biggest effect. It seems to exist an optimal subside payment level out of a fairness perspective which is between 20% and 40% of the actual market prize. Nevertheless, the decision parameter of the regional economic encouragement strategy reveals that the application burdens should be rather higher than lower. The findings for the spatial externality avoidance strategy are not so straightforward to interpret. In general the main effects of the tax level parameter and the spatial externality avoidance strategy decision parameter allow similar interpretations like for the parameters of the spatial externality avoidance strategy, however, the variation impact seems to be lower.

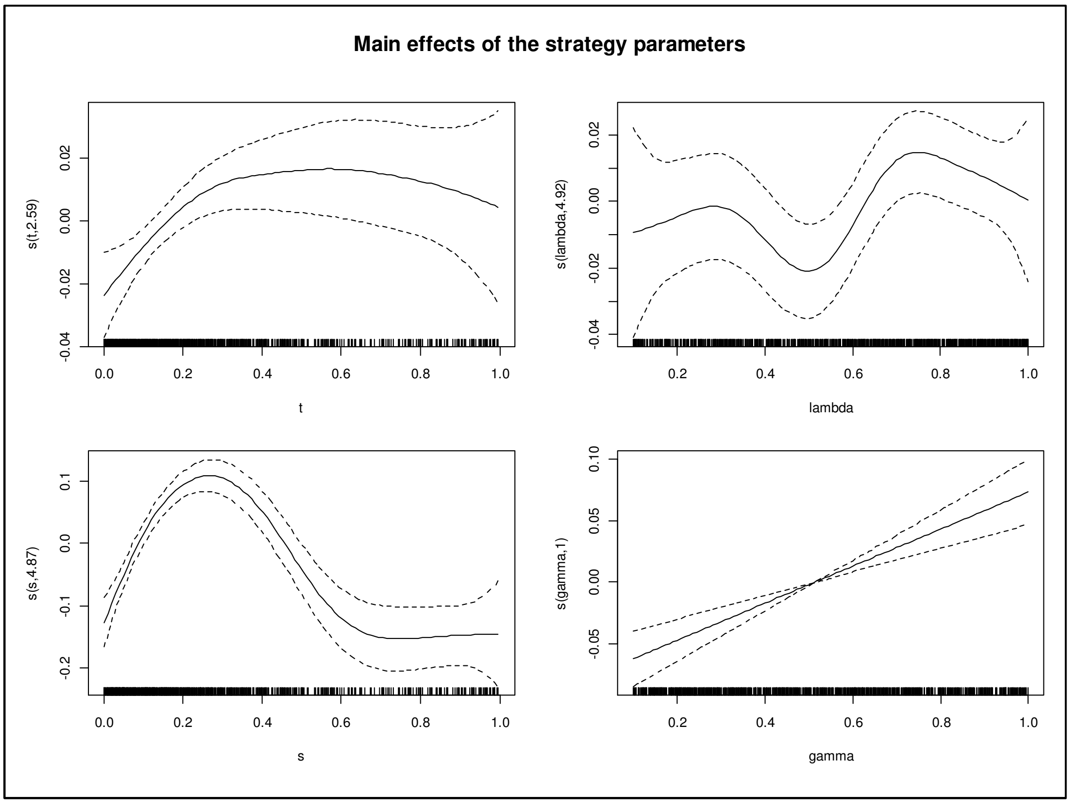


Figure 47: Resulting main effects after the application of the GAM for the tax and subsidy level and the strategy decision parameter λ and γ as explanatory variables and Δw as dependent variable

6.7 Summary and conclusion

The objective of the model analysis of chapter 6 has been the combination of a regional specific strategy choice with an applied mix of policies against the background of (i) regional differences concerning the physical endowment, (ii) the electricity demand and (iii) the regionally specific RES multiplier effects. The implemented policies and the regionally specific properties have been inspired by the German case study.

But before the impact of the spatial externality avoidance strategy or regional economic encouragement strategy has been evaluated, the general efficiency and fairness effects of the introduced *Policy Mix*, consisting of a regulation-based and an additional market-based policy, have been analysed. In general a producer surplus decrease due to a reduction of windfall profits has been observed. Therefore, an average decrease of the production efficiency per wind power plant leads to more wind mill installations with the consequence of increasing spatial externalities.

However, the spatial externality increase could be reduced because of the regulation-based land-use designation policy. Furthermore, a significant grid reinforcement costs reduction has been observed. Consequently, a profit re-allocation between the producers and the consumers has been detected without affecting the overall efficiency, whereas the fairness is affected in a positive manner.

Then the regions were able to apply in a first step the spatial externality avoidance strategy and in a second step the regional economic encouragement strategy if the defined application criteria of section 5.3 were reached. As the *Policy Mix* significantly reduced the grid reinforcement costs, which have been defined within section 5.2 as coalition formation costs, the regional strategy application led to a significant general efficiency reduction by relatively low initial grid reinforcement costs. Therefore, it can be argued that the policy design of a country strongly affects the efficiency and fairness impact of regional strategy implications, as both measures redistribute the benefits not only between the regions (North, South East and South West) but also between the participating agent groups (RES producers and consumer centres).

Accordingly, a spatial externality avoidance strategy may reduce the spatial externalities and therefore the negative consumer centre impact, but it leads at the same time to a producer surplus reduction due to the implementation of a regional tax which affects the benefits negatively. Consequently, the Bavarian alteration of the building code (BayBo 2014) (discussed in chapter 5), which increases the distance of future wind mills to the closest settlement up to ten times (10-H-Abstandsregelung) of the wind mill's hub height (§ 82 and § 83 BayB), redistributes regional benefits between the producers and the consumers, as it is now much harder for the producers to secure areas for the installation of wind mills. But on the other side it avoids negative ecological and social consequences due to new wind power plant installations.

In the case of the introduction of an additional regional subsidy, the wind power plant installations may increase within the particular region, but the additional costs for the subsidy and the higher spatial externality impact have to be overcompensated by a local multiplier effect. Accordingly, a sufficient number of regional agents have to benefit from the higher deployment rates to guarantee a positive regional welfare impact. That can be for example the case if a local production company strongly increases its orders due to new deployments.

Nevertheless, the precise strategy impact depends on the design of an application assumption and the defined tax or subsidy level within the ABM. Consequently, even if the average efficiency impact appears to be negative, a positive regional and generally positive efficiency impact is still possible depending on the defined setting. But due to the different regional properties the outcome will still differ between the regions in such a case.

<u>Chapter 7</u>

Discussion and synthesis

7 Discussion and synthesis

7.1 Summary

The thesis focuses on spatial allocation problems of renewable energy sources in form of wind power plants. Therefore, spatially important aspects of the energy transition process have been analysed and implemented in an agent based model (ABM) platform in order to identify efficient and fair allocation rules considering beside market-based and regulation-based policies also strategically regional behaviour. The presented agent-based model allows us to analyse the consequences on the spatial allocation of sustainable electricity infrastructures by testing a variety of policy scenarios. Accordingly, the model focuses on: (I) agent behaviour of producers and consumers, (II) the overall costs functions that represent all types of costs (including especially spatial externalities), and (III) the constraint of ensuring a given electricity supply for a virtual landscape with renewables.

Various aspects have to be considered while analysing the spatial allocation of the RES infrastructure. One of the most obvious spatially relevant elements is the distribution of the physical endowment (wind conditions and solar radiations). The areas with the most favourable physical conditions can seldom be found in the direct neighbourhood of the existing conventional plants or the demand centres. Accordingly, new electricity production patterns due to deployment of RES appear and make an adaption of the distribution infrastructure in form of the existing grid system necessary, in order to guarantee the permanent supply of the electricity demand. Consequently, the site assessment of the RES producer does not only determine the resulting individual benefit of a RES plant, but also a significant impact on the whole electricity supply side can be observed.

Additionally to the relevant techno-economic effects, RES also have direct site specific social and ecological consequences. In terms of wind power several aspects are discussed in the literature, like the increase of the collision risks for bad and bird species, the noise emissions or the negative aesthetic impact of wind mills. Consequently, negative site- and distance-dependent externalities on a local scale have to be considered in order to asses all relevant spatial costs within the allocation mechanism. But regions are not only confronted with the spatial external costs considered with the energy transformation process, they can also benefit from regional RES plants within their catchment areas. New RES installations typically increase regional business taxes. Furthermore, the new plants have to be operated and maintained. These services are often provided by regional businesses with their employment stock. All these mentioned positive regional economic aspects are defined for the thesis framework as RES related regional multiplier effects.

In the ABM, all above mentioned spatially relevant aspects are implemented. The following model entities are used: a virtual landscape, three settlements as demand centres (consumer centres with catchment areas defined as regions) and profit-oriented producers of renewable power. For the design of the electricity grid and the calculation of grid-related reinforcement costs a load-flow model is applied being also able to map grid externalities during the RES expansion in space. This model is based on an interdisciplinary discussion process linking economic theory to land-use decision modelling and load flow modelling in order to implement all mentioned aspects and therefore to enhance the system understanding for allocation mechanisms of electricity infrastructure. The model has been implemented in R (R DEVELOPMENT CORE TEAM 2013) and NetLogo (Wilensky 1999), whereas NetLogo serves as graphical user interface (GUI) and R is used for the model itself and for the statistical examination of the produced model samples.

After the model construction and the application of plausibility checks, based on reasonable criteria for the various model outcomes in order to rule out potentially unrealistic model behaviour, the performance of different market-based and regulation-based policies has been evaluated. Accordingly, policy scenarios have been defined as a set of rules allocating welfare-relevant costs and benefits across actors in a particular way or a regulation which aims at avoiding externalities.

However, RES spatial allocations are not only driven by the implemented overall policies, but also by the strategic consideration of the affected regions (consumer centres with their corresponding catchment areas) matter. This is even more the case with the presence of coalition formation costs, which can be found in the model context in form of the grid reinforcement costs. Accordingly, two regionally specific strategies have been implemented and investigated. The spatial externality avoidance strategy defines a situation in which a region is not willing to accept more RES installations within its defined catchment area due to an increase of spatial externalities above a defined maximum. In contrast to the spatial externality avoidance strategy the business supports strategy seeks for more investments within its catchment area in order to benefit from the regional multiplier effect of RES due to an increase of tax revenues and potential job maintenances.

The performance of each policy scenario and the regional strategy application can be assessed within the ABM framework under the aspect of an overall efficiency of the virtual energy landscape and a distributional fairness among regions. But to get a complete picture the interdependencies between different model parts have to be analysed. As the conceptual ABM is based on stylised facts the sensitivity of a deduced plausibly parameter set has to be evaluated. Moreover, an ordinary least square (OLS) model has been used together with a flexible generalised additive model (GAM) approach coming from the field of machine learning to analyse computed model samples based in each case on 1000 Monte Carlo Simulations. In the following section the most important scientific results will be briefly discussed.

7.2 Lessons from the ABM

In a first step a basic market-scenario with a uniform feed-in support mechanism, defined as *Market I*, has been evaluated in chapter 3. The encountered parameter effects on the efficiency and fairness have been consistent with real world observations and initial expectations. Right after the first statistical sample evaluation a high importance of the distribution of the physical conditions (wind, solar) has been observed within the model framework, which also can be proven by empirical findings (Ek et al. 2013; Hitaj 2013). Furthermore, the harvest potential determines the resulting production patterns and therefore the distribution costs implicated by the grid costs.

The model distinguishes between connection grid costs and reinforcement grid costs (Barth, Weber et al. 2008), whereas the reinforcement costs are more relevant for an overall economical consideration. If a landscape only provides favourable RES production conditions in a certain area, the producers tend to install the majority of new RES capacities in this particular region, due to higher expected individual profits. According to the following centralisation in one region the grid infrastructure has to be reinforced to guarantee the distribution of the additionally produced electricity coming from RES to the remaining landscape areas. Therefore, grid reinforcement costs increase if production patterns tend to be centralised. Accordingly, grid expenses can be decreased if the general distance between the electricity demand and the supply can be reduced. However, resulting spatial externality and plant efficiency changes have to be considered in order to determine the overall welfare impact of such measures.

To reallocate certain cost elements between the consumer and the producer or to alter the producer’s site-assessment mechanism in order to avoid spatial externalities, various policy settings in form of policy scenarios can be tested within the ABM framework. Certain policies can improve the overall efficiency or fairness. In general some can argue that they increase the producer´s responsibility in order to choose sites with a higher economic value in terms of a reinforcement and spatial costs avoidance.

The first policy outcomes have been obtained in the field of regulation-based policies by examining land-use restriction and land-use designation policies in the section 4.2. Therefore, the land-use restriction or designation level has been altered between 0% and 100% within 1000 Monte Carlo simulations. Except of harvest-dependent land-use designations we observe an average positive efficiency effect at moderate restrictions or designation levels and the highest fairness increase. At high restriction levels the spatial externality savings will be compensated by the decrease of production efficiency due to chosen production sites with less favourable physical conditions. Accordingly, we observe an efficiency-fairness trade-off (Bertsimas et al. 2012) for the application of effective regulation-based policies. These findings are consistent with the economic literature, where more regulations or planning lead to an efficiency decrease whereas the societal fairness increases. Consequently, effective regulation-based policies are a very useful tool to avoid spatial externalities. Furthermore, they can lead to more harmonised production structures where the wind mill plants will be distributed more evenly. However, it is not enough to focus on the physical potential for the design of such policies also societal and ecological information, like the settlement-plant distance or the ecological vulnerability have to be taken into account.

In the next step additional market-based policies have been tested within a similar analytic framework in section 4.3. At the beginning the homogenous RES support scheme, consisting of uniform payments, has been extended by a reference yield mechanism in subsection 4.3.2. Now the support scheme is aligned to the electricity returns of a defined reference plant. Two major objectives are connected to such a mechanism. Firstly high windfall profits should be avoided for producer plants within exceptionally good areas. Secondly the deployment of RES plants should be possible at a broader regional scale to support a comprehensive supply of RES within all regions. Different reference yield designs regarding the shape of the reference yield function, which determines the average payment per harvest unit per site, have been tested with the result that the slope parameter has a significant impact on the efficiency and fairness outcomes. Therefore, a well-designed reference yield model can significantly reduce the grid costs. Nevertheless, alternative spatial RES plant allocations lead to efficiency losses which vice versa result in more RES plant installations. If that is the case, the spatial externalities increase for the overall virtual landscape with the consequence that the consumer centre’s regional net utility, which contains the regional consumer surplus minus the regional externalities, declines. Again a trade-off can be observed, but this time between grid externalities and spatial externalities. Accordingly, the mechanism only leads to an overall efficiency increase if the grid cost savings are higher than the additional spatial externalities.

The next analysis dealt with the implementation of a nodal pricing mechanism within the subsection 4.3.3. Consequently, a certain amount of the grid reinforcement costs have been reallocated from the consumers to the producers with the objective that producers get additional location specific information about the grid suitability of a potential renewable plant location. This locational electricity pricing (LEP) can be distinguished in a marginal and long term cost component. For simplification reasons we determine a reinforcement cost share which determines the producer ratio on this particular grid cost element. The produced samples with different initial grid structures reveal a high impact on the efficiency even with relatively low producer cost shares up to 20%. A further advantage is the lack of negative response by other welfare relevant elements. Accordingly, we do not observe any significant impact, neither on the spatial externalities nor on the fairness parameter. Regarding the statistical evaluation of the model sample a nodal or zonal pricing mechanism, which only focuses on the marginal network costs elements, would lead to a significant welfare improvement.

After the examination of market and regulation based policies the strategic behaviour of the consumer centres with their particular catchment areas (defined as regions) have been further analysed in chapter 5. Region specific behaviour is not uncommon in the realm of the energy transition. Due to very restricted land-use policies or additional impedance during the planning procedure of a RES plant, regions can take measure to slow down RES capacity deployments. But also contrary examples with additional regional support strategies can be found in form of defined energy regions.

In a first step the cooperative game theoretical approach has been rejected, as initial analysis revealed a violation of the superadditvity assumption for the ABM approach if distribution costs in form of grid reinforcement costs arise. Accordingly, these costs can be defined as coalition formation costs. But to consider this deliberation within the ABM framework a spatial externality avoidance and a regional economic encouragement strategy, besides the primary participation in a grand supply coalition, have been introduced in second step in section 5.3. Therefore, assumptions for the application of a certain strategy have been defined. Accordingly, the spatial externality avoidance strategy, consisting of additional regional producer tax per demand unit, will be applied if a region faces high spatial externalities. The regional economic encouragement strategy, connected with an additional subsidy per demand unit, will be applied if the region consumer surplus falls under a defined level. For the sample different values within a defined range for the strategy application parameter, the tax and the subsidy level has been used.

Both strategies can increase the average welfare of a sample by absence of any additional regulation- or market policy. In case of the spatial externality avoidance strategy we observe a trade-off between a decreasing producer surplus and an increasing consumer surplus, which can be mainly explained by reinforcement cost savings, because the regional opportunity to implement taxes to slow down the RES deployment can be seen as a concentration impedance for new RES plants. Thereby the tax level does not have any significant impact on the efficiency, but the strategy application parameter does. Accordingly, a local maximum has been observed within the main effects of the GAM. For the regional economic encouragement strategy we observe a similar but reversed producer consumer surplus trade-off. This time the producer benefits from the strategy application and consumer have to give up a part of their surplus to finance the additional regional RES incentive with the consequence that now both, the subsidy and the strategy decision parameter, are significant, so that a higher parameter leads to a higher welfare improvement, whereas the maximum is reached at one for the strategy application parameter, which would lead to an immediate regional economic encouragement strategy application of all regions. Now, producers receive additional diffusion incentives if the regional economic encouragement strategy will be applied by a region. As reinforcement costs savings are the main sources for potential welfare improvements, the positive welfare impact increases proportionally to the computed reinforcement costs at the business as usual scenario, where no regional strategies are allowed.

Finally the spatial externality avoidance and regional economic encouragement strategy have been applied in the context of the case study Germany in chapter 6. Therefore, regional stylized facts have been deduced from empirical information in order to represent three different regions which show significant region specific variations. Furthermore, a *Policy Mix* has been implemented out of already analysed regulation-based and market-based policies to come closer to the policy conditions in Germany. The examination reveals a similar average reversed effect of the spatial externality avoidance and regional economic encouragement strategy, like in chapter 5. However, the regional impact strongly depends on the design of the *Policy Mix*, the general properties of the region (wind conditions, electricity demand, ecological sensibility and economic structure) and on the strategic reaction of the remaining regions, as all measures redistribute the benefits not only among the regions but also among the participating agent groups.

7.3 Reflection on the methodological approach

The RES spatial allocation problem has been modelled using an ABM approach. Due to the flexibility of ABM, it has been possible to combine economic, engineering and geographic elements to complement existing frameworks leading to a more comprehensive system understanding of policy mechanisms and regionally specific strategic considerations. Nowadays it is not uncommon to use ABMs in order to get insights about policy mechanisms. For example many authors (Berger 2001; Berger, Schreinemachers et al. 2006; Happe, Kellermann et al. 2006; Hartig and Drechsler 2009; Filatova, Voinov et al. 2011; Zhang, Zhang et al. 2011; Polhill, Gimona et al. 2013; Sun and Müller 2013) have attributed ABM based policy analyses for various research fields.

Due to the economic basis it has been possible to implement a consistent terminology like welfare, producer surplus, consumer surplus and externalities in order to evaluate and understand the model results. To address spatial heterogeneity map algebra elements, like raster based least cost path calculations (Pinto and Keitt 2009) coming from geography, have been added and for the design of the grid infrastructure a simple DC-Load Flow model (Nolden, Schönfelde et al. 2013), which is typically used for techno-economic analysis, has been implemented. Accordingly, the model uses the strength of various disciplines to create an interdisciplinary framework, which has a spatial context, and is based on bottom-up procedures with implemented adaptive agents. Therefore, it unites some of the advantages which are typical for ABMs. They are pointed out by Crooks and Heppenstall (2012).

Nevertheless, the presented model did not make use of the complete range of benefits which can be determined by an ABM framework. Despite the introduction of regional strategies for the consumer centres, the human decision model is based on a standard neo-classical assumption. For example possibilities, like uncertainty, satisfying mechanism or learning aspects in the context of agent decisions (Nolan et al. 2009), are not addressed within the model framework. Accordingly, agents behave fully rational and fully informed. On the one hand that helps to reduce the complexity of the ABM, which again helps to produce robust results. But on the other hand important decision mechanism may left out.

The use of NetLogo and R connected by the RNetLogo package developed by Thiele (2012) as analytic platform provides various advantages. Firstly NetLogo can be used as GUI for a better visualisation of the allocation process and secondly the link between both programmes guarantees the access to the broad pool of developed R-packages which facilitate the construction and evaluation process. However, a performance disadvantage has been determined due to the communication between NetLogo and R. Parallel programming and the usage of several CPUs help to overcome these difficulties. For very complex model frameworks, however, the usage of object-oriented programming languages, like Java and C++, is preferable.

To get new insights from the ABM, global sensitivity analyses, which have been evaluated with the help of OLS and GAM, have been applied. For the sample generation 1000 Monte Carlo simulations have been performed with predefined basic parameter intervals. The application of a statistically advanced machine learning algorithm, like the GAM developed by Hastie and Tibshirani (1986), helped to compute non-linear main effects of the determined parameters. Therefore, trade-off and eventual tipping points can be identified, which increases the general system understanding. Nevertheless, the conceptual model design does not provide case specific recommendations, which can only be provided by a more empirically based model framework, which helps to reduce the overall model uncertainty.

7.4 Outlook

This section 7.4 deals with further model extensions for the ABM framework in order to address additional research questions which are directly or indirectly related to spatial allocation mechanisms of RES. Therefore, we can distinguish between two expansion options. Firstly, (i) we can add further policies and strategies within the existing ABM framework or further analyses potential trade-offs between the already examined policies or strategies. Secondly, (ii) we can extend the existing ABM framework with reasonable additional modules which increase the complexity of the whole approach.

Furthermore, the theoretical concept of the developed ABM framework can be used for a GIS-based empirical approach for a defined region. But despite the availability of precise spatial data concerning RES potentials, settlement areas and the grid infrastructure for the German case study not all spatial externalities, include in the ABM, could be addressed by a complete empirical basis (landscape sensibility, aesthetic values). Moreover, such an approach would lack flexibility regarding policy and strategy evaluation, due to its necessary complexity. Consequently, the outlook section will focus on the ABM’s extension opportunities.

The ABM has allowed the evaluation of different defined policy and strategy scenarios. Except for the last chapter 6 where the trade-offs between existing German policies and the regional strategies have been examined, all other policies and strategies have been evaluated on their own without having taken further trade-offs among these scenarios into account. It would e.g. be possible to have a closer look at the interaction between market-based and regulation-based policy options, or to find out what happens if consumer centres have the possibilities to flexible choose (non-static determination of tax and subsidy rates) between all strategies within one strategy scenario.

In the context of a model based evaluation of real world problems, models will always have certain limitations and therefore tend to simplify complex issues. Accordingly, model extensions are always under discussion. For our ABM approach we followed the KISS principle, which is an acronym for: “Keep it simple, stupid!” (Axelrod 1997). Only modules and entities, which are spatially relevant for dealing with the questions of the spatial allocation mechanism of RES, have been included into the abstract model design. Nevertheless, further extensions concerning the agent design, the market mechanism and the temporal model mechanism can improve the explanatory power, but they also bear the risk of a higher model complexity in which it is harder to detect system relevant context knowledge within the random noise.

It would make sense to improve the general agent design of the producer and consumer centre. Therefore, a certain degree of producer heterogeneity could be introduced regarding the production types (wind, biomass, solar) and the production size (small, medium, big). That would allow a more realistic illustration of all RES, with particular properties concerning their impact on the supply, the regional multiplier effect and the spatial externalities. Moreover, the agent decision model could be extended from completely rational to rather bounded rational actors, by implementing defined producer scopes or the integration of benefit uncertainty, which would allow negative producer benefits. Consequently, a higher dynamic concerning the electricity production patterns would be generated, which would also allow the consideration of the electricity production plant’s operation life. Besides the agent design also the market mechanisms of the model could be improved. Despite focussing on spatial allocation mechanisms a complete integration of an electricity market would allow to take electricity efficiency efforts of the consumers into account. That would again allow the implementation of further consumer related policies within the ABM framework. Another important aspect which has been left out in the presented model design, are the volatile RES production patterns. The electricity supply of wind power plants and photovoltaic cells is not baseload compatible, as such plants only produce electricity if the wind is blowing or the sun is shining. First of all the implementation of volatile electricity patterns would have dramatically increased the model complexity. Furthermore, we argue that the resulting supply demand mismatches can be levelled out by good grid infrastructure for a certain degree and that future storage systems will be located close to the RES productions. Therefore, the volatility aspect is indeed very important for the transition of the electricity sector, but it plays a minor role in terms of the spatial allocation mechanism of RES, considering efficiency and fairness aspect among regions and the considered agents.

References:

AGORA (2013): Kostenoptimaler Ausbau der Erneuerbaren Energien in Deutschland - Ein Vergleich möglicher Strategien für den Ausbau von Wind- und Solarenergie in Deutschland bis 2033. Berlin, Agora Energiewende, Consentec GmbH, Frauenhofer IWES.

AGORA (2014): Vergütung von Windenergieanlagen an Land über das Referenzertragsmodell. Berlin.

Anselin, L. (2003): Spatial externalities. International Regional Science Review 26(2): 147-152.

Apt, K. R. and A. Witzel (2009): A generic approach to coalition formation. International Game Theory Review 11(03): 347-367.

Aretz, A., et al. (2013): Wertschöpfung durch erneuerbare Energien – wie Bundesländer profitieren. GAIA 22/1: 46 -54.

Axelrod, R. (1997): The complexity of cooperation, Princeton university press Princeton.

Baban, S. M. J. and T. Parry (2001): Developing and applying a GIS-assisted approach to locating wind farms in the UK. Renewable Energy 24(1): 59-71.

Baeyens, E., et al. (2013): Coalitional aggregation of wind power. Power Systems, IEEE Transactions on 28(4): 3774-3784.

Barth, R., et al. (2008): Distribution of costs induced by the integration of RES-E power. Energy Policy 36(8): 3107-3115.

BayBo (2014): Bavarian Building Code.

Berger, T. (2001): Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. Agricultural economics 25(2): 245-260.

Berger, T., et al. (2006): Multi-agent simulation for the targeting of development policies in less-favored areas. Agricultural Systems 88(1): 28-43.

Bertsimas, D., et al. (2012): On the efficiency-fairness trade-off. Management Science 58(12): 2234-2250.

Bhakar, R., et al. (2010): Probabilistic game approaches for network cost allocation. Power Systems, IEEE Transactions on 25(1): 51-58.

BImSchG (2014): Federal Pollution Control Act Germany.

Bitar, E. Y., et al. (2012): Optimal sharing of quantity risk for a coalition of wind power producers facing nodal prices. American Control Conference (ACC), 2012, IEEE.

Blaschke, T., et al. (2013): 'Energy landscapes': Meeting energy demands and human aspirations. Biomass and Bioenergy 55(0): 3-16.

Blesl, M., et al. (2007): Role of energy efficiency standards in reducing CO2 emissions in Germany: An assessment with TIMES. Energy Policy 35(2): 772-785.

BMU (2013): Potential der Windernergie an Land. Dessau-Roßlau, Umwelt Bundes Amt.

BMU/BMWi (2010/11). "Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung.". Retrieved 02.04., 2013, from: http://www.bmu.de/fileadmin/bmuimport/files/pdfs/allgemein/application/pdf/energiekonzept_bundesregierung.pdf.

BMVBS (2013): Regionalwirtschaftliche Effekte der erneuerbaren Energie II. Einfluss der Regionalplanung und Raumordnung auf regionale Wertschöpfung. BMVBS-Online-Publikation 22/2013.

BNatSchG (2013): Federal act for the protection of Nature Germany.

BnetzA (2013): Genehmigung des Szenarienrahmens zum Netzenwicklungsplan (NEP) 2013. Bundesnetzagentur.

Bosch, S. (2012): Erfassung und Bewertung des Einflusses der Ressource Raum im Rahmen der Förderung von Erneuerbaren Energien sowie Ableitung eines ganzheitlichen Ansatzes zur optimalen Integration von regenerativen Technologien in den ländlichen Raum. Augsburg.

Bosch, S., Peyke, G. (2011): Raum und Erneuerbare Energien, Anforderungen eines regenerativen Energiesystems an die Standortplanung. Standort 34: 11 - 19.

Brandstätt, C., et al. (2011): Locational signals to reduce network investments in smart distribution grids: what works and what not? Bremen Energy Working Papers No. 7(Bremer Energie Institut).

Bright, J., et al. (2008): Map of bird sensitivities to wind farms in Scotland: A tool to aid planning and conservation. Biological Conservation 141(9): 2342-2356.

Brücher, W. (2009): Energiegeographie: Wechselwirkung zwischen Ressourcen, Raum und Politik. Berlin, Bornträger.

Bunn, D. W. and F. S. Oliveira (2001): Agent-based simulation-an application to the new electricity trading arrangements of England and Wales. Evolutionary Computation, IEEE Transactions on 5(5): 493-503.

Chappin, E. J. L. and G. P. J. Dijkema (2010): Agent-based modelling of energy infrastructure transitions. Int. J. Critical Infrastructures 6(2): 106-130.

CONSENTEC, E., IAEW (2008): Analyse und Bewertung der Versorgungssicherheit in der Elektrizitätsversorgung (Monitoringbericht nach §51 EnWG). Berlin, Bundesministerium für Wirtschaft und Technologie (BMWi).

Contreras, J., et al. (2009): An incentive-based mechanism for transmission asset investment. Decision Support Systems 47(1): 22-31.

Couture, T. and Y. Gagnon (2010): An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. Energy Policy 38(2): 955-965.

Cowell, R. (2010): Wind power, landscape and strategic, spatial planning—The construction of ‘acceptable locations’ in Wales. Land Use Policy 27(2): 222-232.

Crooks, A. and A. Heppenstall (2012): Introduction to Agent-Based Modelling. Agent-Based Models of Geographical Systems. A. J. Heppenstall, A. T. Crooks, L. M. See and M. Batty, Springer Netherlands: 85-105.

Csardi, G. and T. Nepusz (2006): The igraph software package for complex network research. InterJournal, Complex Systems 1695(5): 1-9.

DENA (2010): DENA-Netzstudie II: Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015–2020 mit Ausblick 2025. Berlin, DENA.

Devine-Wright, P. (2011): From Backyards to Places: Public Engagement and the Emplacement of Renewable Energy Technologies. Renewable Energy and the Public: From NIMBY to Participation. P. Devine-Wright. London, earthscan.

Drechsler, M., Ohl, C., Meyerhoff, J., Eichhorn, M., Monsees, J. (2011): Combining spatial modeling and choice experiments for the optimal spatialal location of wind turbines. Energy Policy 39: 3845 -3854.

Duthaler, C. F. (2007): Power Transfer Distribution Factors: Analyse der Anwendung im UCTE-Netz, Eidgenössische Technische Hochschule Zürich.

DWD (2014): Data on average wind power (80 meters) between 1981 and 2001. G. W. S. (DWD).

EEG (2000): Renewable Energy Support Act. Germany.

EEG (2014): Renewable Energy Source Act. Germany.

Eichhorn, M. and M. Drechsler (2010): Spatial trade-offs between wind power production and bird collision avoidance in agricultural landscapes. Ecology and Society 15(2): 10 - 21.

Ek, K., et al. (2013): Location of Swedish wind power—Random or not? A quantitative analysis of differences in installed wind power capacity across Swedish municipalities. Energy Policy 58(0): 135-141.

Elberg, C. and S. Hagspiel (2015): Spatial dependencies of wind power and interrelations with spot price dynamics. European Journal of Operational Research 241(1): 260-272.

Faruqui, A., et al. (2009): The Power of Dynamic Pricing. The Electricity Journal 22(3): 42-56.

Filatova, T., et al. (2011): Land market mechanisms for preservation of space for coastal ecosystems: An agent-based analysis. Environmental Modelling & Software 26(2): 179-190.

Frey, B. S. and F. Oberholzer-Gee (1997): The cost of price incentives: an empirical analysis of motivation crowding out. American Economic Review 87: 746 - 755.

Fujita, M., et al. (2001): The spatial economy: Cities, regions, and international trade, MIT press.

Gawel, E. and A. Purkus (2013): Promoting the market and system integration of renewable energies through premium schemes—A case study of the German market premium. Energy Policy 61: 599-609.

George, W., et al. (2009): Regionale Energieversorgung, Chance für eine zukunftsfähige Ziel- und Ressourcensteuerung in der Energiewirtschaft. Angewandte Geographie 33: 13 -21.

Grimm, V., et al. (2010): The ODD protocol: A review and first update. Ecological Modelling 221(23): 2760-2768.

Grimm, V., et al. (2005): Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons from Ecology. Science 310(5750): 987-991.

Groothuis, P. A., et al. (2008): Green vs. green: Measuring the compensation required to site electrical generation windmills in a viewshed. Energy Policy 39: 503 - 510.

Gross, R. (2006): The Costs and Impacts of Intermittency: An assessment of the evidence on the costs and impacts of intermittent generation on the British electricity network, UK Energy Research Centre.

Grothe, O. and J. Schnieders (2011): Spatial dependence in wind and optimal wind power allocation: A copula-based analysis. Energy Policy 39(9): 4742-4754.

Haller, M., et al. (2012): Decarbonization scenarios for the EU and MENA power system: Considering Spaital distribution and short term dynamics of renewable generation. Energy Policy 47: 282 - 290.

Happe, K., et al. (2006): Agent-based Analysis of Agricultural Policies: an Illustration of the Agricultural Policy Simulator AgriPoliS, its Adaptation and Behavior Ecology and Society 11(1)(49).

Hartig, F. and M. Drechsler (2009): Smart spatial incentives for market-based conservation. Biological Conservation 142(4): 779-788.

Hasan, K. N., et al. (2014): Benefit-based expansion cost allocation for large scale remote renewable power integration into the Australian grid. Applied Energy 113: 836-847.

Hastie, T. and R. Tibshirani (1986): Generalized Additive Models. Statistical Science 1(3): 297 - 318.

Hastik, R., et al. (2015): Renewable energies and ecosystem service impacts. Renewable and Sustainable Energy Reviews 48: 608-623.

Heppenstall, A. J., et al. (2012): Agent-Based Models of Geographical Systems, Springer Netherlands.

Hijmans, R. J. (2015): Introduction to the’raster’package (version 2.3-40).

Hirschl, B., et al. (2011): Regionalökonomische Effekte Erneuerbarer Energien, kommunale Wertschöpfung und Beschäftigung durch dezentrale Energieerzeugung. Solarzeitalter. 3.

Hirschl, B., et al. (2010): Kommunale Wertschöpfung durch Erneuerbare Energien. Schriftenreihe des IÖW 196(10).

Hitaj, C. (2013): Wind power development in the United States. Journal of Environmental Economics and Management 65(3): 394-410.

Holttinen, H., et al. (2011): Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration. Wind Energy 14(2): 179-192.

IOER (2015): Landscape protection area, The Leibniz Institute of Ecological Urban and Regional Development.

Jobert, A., Laborgne, P., Mimler, S. (2007): Local acceptance of wind energy: Factors of success identified in French and German case studies. Energy Policy 35: 2751 -2760.

Joskow, P. L. (2011): Comparing the costs of intermittent and dispatchable electricity generating technologies. The American Economic Review 101(3): 238-241.

Kikuchi, R. (2008): Adverse impacts of wind power generation on collision behaviour of birds and anti-predator behaviour of squirrels. Journal for Nature Conservation 16(1): 44-55.

Kitzing, L., et al. (2012): Renewable energy policies in Europe: Converging or diverging? Energy Policy 51: 192-201.

Kleijnen, J. P. (2007): Design and analysis of simulation experiments, Springer Science & Business Media.

Kosfeld, R., Gückelhorn, F. (2011): Ökonomische Effekte erneuerbarer Energien auf regionaler Ebene. Raumforschung und Raumordnung 70: 437 - 449.

Krewitt, W., et al. (2011): Analyse von Rahmenbedingungen für die Integration erneuerbarer Energien in die Strommärkte auf der Basis agentenabsierter Simulation. Stuttgart, Vilshofen, Saarbrücken.

Krugman, P. (1999): Development Geography and Economic Theory. Cambridge, London, The MIT Press.

Kunreuther, H., et al. (1987): A compensation mechanism for siting noxious facilities: theory and experimental design. Journal of Environmental Economics and Management 14(4): 371-383.

Kunz, T. H., et al. (2007): Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Frontiers in Ecology and the Environment 5(6): 315-324.

Kuvlesky, W. P., et al. (2007): Wind Energy Development and Wildlife Conservation: Challenges and Opportunities. The Journal of Wildlife Management 71(8): 2487-2498.

Langendörfer, U. (2012): Flächenpotentialanalyse ERNEUERBAR KOMM! Erneuerbare Energie unterstützt durch GIS und Landmanagement. Frankfurt am Main, Klärle, M. .

Lehr, U., et al. (2015): Beschäftigung durch erneuerbare Energien in Deutschland: Ausbau und Betrieb, heute und morgen. Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie, Osnabrück, Berlin, Stuttgart.

Lejano, R. P. and C. A. Davos (2002): Fair Share: Siting Noxious Facilities as a Risk Distribution Game under Nontransferable Utility. Journal of Environmental Economics and Management 43(2): 251-266.

Lesser, J. A. and X. Su (2008): Design of an economically efficient feed-in tariff structure for renewable energy development. Energy Policy 36(3): 981-990.

Leuthold, F., et al. (2005): Nodal Pricing in the German Electricity Sector-A Welfare Economics Analysis, with Particular Reference to Implementing Offshore Wind Capacities. Available at SSRN 1137382.

Leuthold, F., et al. (2008): Efficient pricing for European electricity networks – The theory of nodal pricing applied to feeding-in wind in Germany. Utilities Policy 16(4): 284-291.

Lewis, G. M. (2010): Estimating the value of wind energy using electricity locational marginal price. Energy Policy 38(7): 3221-3231.

Li, F., et al. (2009): Framework for assessing the economic efficiencies of long-run network pricing models. Power Systems, IEEE Transactions on 24(4): 1641-1648.

Ma, T. and Y. Nakamori (2009): Modeling technological change in energy systems – From optimization to agent-based modeling. Energy 34(7): 873-879.

Meyerhoff, J., et al. (2010): Landscape externalities from onshore wind power. Energy Policy 38(1): 82-92.

Mills, A. D. and R. H. Wiser (2012): Changes in the economic value of photovoltaic generation at high penetration levels: A pilot case study of California. Photovoltaic Specialists Conference (PVSC), Volume 2, 2012 IEEE 38th, IEEE.

Neddermann, B. (2014): EEG 2014 -New Framework Conditions for Wind Energy Use in Germany. DEWI Magazin 45: 51-55.

Neumann, J. and O. Morgenstern (1944): Theory of games and economic behavior. Princeton,, Princeton university press.

Nicolosi, M. (2012): The economics of renewable electricity market integration. An empirical and model-based analysis of regulatory frameworks and their impacts on the power market, Universität zu Köln.

Nolan, J., et al. (2009): An overview of computational modeling in agricultural and resource economics. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 57(4): 417-429.

Nolden, C., et al. (2013): Network constraints in techno-economic energy system models: towards more accurate modeling of power flows in long-term energy system models. Energy Systems 4(3): 267 -287.

Ohl, C. and M. Eichhorn (2010): The mismatch between regional spatial planning for wind power development in Germany and national eligibility criteria for feed-in tariffs—A case study in West Saxony. Land Use Policy 27(2): 243-254.

Osborne, M. J. and A. Rubinstein (1994): A course in game theory. Cambridge, Mass., MIT Press.

Overbye, T. J., et al. (2004): A comparison of the AC and DC power flow models for LMP calculations. 37th Hawaii International Conference on System Sciences.

Phillips, B. R. and R. S. Middleton (2012): SimWIND: A geospatial infrastructure model for optimizing wind power generation and transmission. Energy Policy 43: 291-302.

Pinto, N. and T. Keitt (2009): Beyond the least-cost path: evaluating corridor redundancy using a graph-theoretic approach. Landscape Ecology 24(2): 253-266.

Plata, A. (2008): Optimale Standorte von Biogasanlagen, Geographische Informationssysteme als entscheidungsunterstützende Instrumente im Bereich Bioenergie. Angewandte Geographie 32: 141 -146.

Polhill, J. G., et al. (2013): Nonlinearities in biodiversity incentive schemes: a study using an integrated agent-based and metacommunity model. Environmental Modelling & Software 45: 74-91.

R DEVELOPMENT CORE TEAM (2013). "R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing." Retrieved 02.09., 2013, from: http://www.r-project.org/.

Rahwan, T., et al. (2015): Coalition structure generation: A survey. Artificial Intelligence 229: 139-174.

Railsback, S. F. and V. Grimm (2012): Agent-Based and Individual-Based Modeling: A Practical Introduction. Princeton, Princeton University Press.

Raumordnungsgesetz (2008): Federal Regional Planning Act. Germany.

Reiche, D. and M. Bechberger (2004): Policy differences in the promotion of renewable energies in the EU member states. Energy Policy 32(7): 843-849.

Remme, U. (2006): Zukünftige Rolle erneuerbarer Energien in Deutschland: Sensitivitätsanalysen mit einem linearen Optimierungsmodell. Institut für Energiewirtschaft. Stuttgart, Universität Stuttgart.

Rodman, L. C. and R. K. Meentemeyer (2006): A geographic analysis of wind turbine placement in Northern California. Energy Policy 34(15): 2137-2149.

Roques, F., et al. (2010): Optimal wind power deployment in Europe—A portfolio approach. Energy Policy 38(7): 3245-3256.

Saad, W., et al. (2009): Coalitional game theory for communication networks. Signal Processing Magazine, IEEE 26(5): 77-97.

Saltelli, A., et al. (2008): Global sensitivity analysis: the primer, John Wiley & Sons.

Saltelli, A., et al. (2000): Sensitivity Anaysis as an Ingredient of Modeling. 377-395.

Schradinger, I. (2008): GIS-gestützte Standortevaluierung für Biogasanlagen im Bundesland Tirol. Angewandte Geoinformatik 2008 – Beiträge zum 20. AGIT-Symposium Salzburg. Salzburg, Strobl, J., Blaschke, T., Griesebner G.: 491 - 500.

Schweppe, F., et al. (1987): Spot pricing of electricity. New York, Kluver Academic.

Selten, R. (2001): Die konzeptionellen Grundlagen der Spieltheorie einst und jetzt. Bonn, Bonn Graduate School of Economics.

Shapley, L. S. and A. E. Roth (1988): The Shapley value : essays in honor of Lloyd S. Shapley. Cambridge Cambridgeshire ; New York, Cambridge University Press.

Silz-Szkliniarz, B. (2013): Energy Planning in Selected European Regions - Methods for Evaluating the Potential of Renewable Energy Sources. Karlsruhe, KIT Scientific Publishing.

Sun, Z. and D. Müller (2013): A framework for modeling payments for ecosystem services with agent-based models, Bayesian belief networks and opinion dynamics models. Environmental Modelling & Software 45: 15-28.

Tabassum, A., et al. (2014): Wind energy: Increasing deployment, rising environmental concerns. Renewable and Sustainable Energy Reviews 31: 270-288.

Thiele, J., Kurth, W., Grimm, V. (2012): Agent-based modelling: Tools for linking NetLogo and R. Journal of Artificial Societies and Social Simulation 15(3): 8.

Thiele, J. C., et al. (2014): Facilitating Parameter Estimation and Sensitivity Analysis of Agent-Based Models: A Cookbook Using NetLogo and 'R'. Journal of Artificial Societies and Social Simulation 17(3): 11.

Thünen, J. (1875): Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie. Darmstadt, Wissenschaftliche Buchgesellschaft.

Toke, D., et al. (2008): Wind power deployment outcomes: How can we account for the differences? Renewable and Sustainable Energy Reviews 12(4): 1129-1147.

Ulrich, P. and U. Lehr (2013): Erneuerbar beschäftigt in den Bundesländern: Bericht zur aktualisierten Abschätzung der Bruttobeschäftigung 2013 in den Bundesländern. Gesellschaft für Wirtschaftliche Strukturforschung, Osnabrück.

van der Horst, D. (2007): NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. Energy Policy 35: 2705 -2714.

van Etten, J. (2012): R Package gdistance: Distances and Routes on Geographical Grids.

Weber, A. (1909): Über den Standort der Industrie. Ertser Teil: Reine Theorie des Standorts. Tübingen, Mohr, Siebeck.

Weigt, H. (2006): A time-variant welfare economic analysis of a nodal pricing mechanism in Germany. Proceeding of the 5th conference on applied infrastructure research.

Wilensky, U. (1999): NetLogo. Northwestern University, Evanston, Center for Connected Learning and Computer-Based Modeling.

WindGuard (2013): Kostensituation der Windenergie an Land in Deutschland. Varel, Deutsche WindGuard GmbH.

Winter, E. (2002): Chapter 53 The shapley value. Handbook of Game Theory with Economic Applications. A. Robert and H. Sergiu, Elsevier. Volume 3: 2025-2054.

Wittmann, T., Bruckner, T. (2007): Agentenbasierte Modellierung urbaner Energiesysteme. Wirtschaftsinformatik 49(5): 352 - 360

Wolsink, M. (2007): Wind power implementation: The nature of public attitudes: Equity and fairness instead of ‘backyard motives’. Renewable and Sustainable Energy Reviews 11(1188 - 1207).

Wood, S. N. (2006): Generalized Additive Models: An Introduction with R. CRC, Chapman and Hall.

Zaspel, B. (2014): Energiewende in Deutschland: Herausforderungen für die Landesplanung, Hannover: Verlag der ARL-Akademie für Raumforschung und Landesplanung.

Zhang, B., et al. (2011): An adaptive agent-based modeling approach for analyzing the influence of transaction costs on emissions trading markets. Environmental Modelling & Software 26(4): 482-491.

Appendix

GitHub Installation Guide

Introduction

This section describes the workflow to run the ABM on your own system. As the model is based on NetLogo (version 5.04) and R (version 3.2.0, 64 bit) both programmes have to be installed on your system before the ABM can be executed. The source code of the ABM can be found on a web-based Git repository hosting service named GitHub via following link:

https://github.com/Tomski85/RESAM

Therefore the Github repository provides you besides all the model modules with various R-scripts which have been used for the model evaluation. To emphasise the thematic focus of the presented ABM we call it *Renewable Energy Spatial Allocation Model* (RESAM) within the GitHub framework and the following sections.

The structure

Besides the readme.md and the RESAM script for R, the repository consists of three folders. The R-Module folder contains the *Grid-Module* and the *Main-Module* together with defined functions for the *Spatial-Module*. In the NetLogo-Module the written NetLogo script can be found.

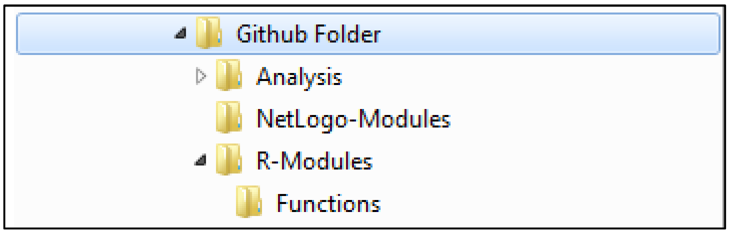


Figure A1: Representation of the folder structure which has to be generated on your system in order to run RESAM

Netlogo and R are connected via the package RNetlogo developed by Thiele et. al (2012). It allows to steer Netlogo from R with specific command lines. Therefore Netlogo serves as graphical user interface (GUI) during a model run. Therefore it does not produce any reliable results if it is executed directly within NetLogo, because not all variables are computed within this single model platform. Nevertheless, a single model run can be observed via NetLogo. The last folder Analysis contains all R scripts which have been applied for the statistical evaluation of produced RESAM samples.

Running RESAM

After the download of the complete repository at a local hard drive, the user can start the RESAM.r file. In a first step all required R packages have to be installed if they are not already part of the local library. Afterwards the downloaded Github folder has to be defined as local workplace.

Within the script the user has the possibility to produce a sample of model runs with a defined parameter set, policy or coalition structure. Consequently, the user can determine the sample size, the policy scenario and the coalition structure of the consumer centres within the script. Furthermore, one can define parameter intervals which will be used to produce a random parameter set per model run.

If the altered script will be completely executed, R will start NetLogo with the RESAM script and it will start to produce a sample of model runs which can be statistically evaluated at the end. Therefore a data frame in the Rdata format will be stored within the defined workspace. It contains the applied parameter set together with all globally and locally computed variables.