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University of Hamburg
Research Group Climate Change and Security

Working Paper
CLISEC-33

Equation Chapter 1 Section 1

They sow the wind and reap bioenergy – Implications of the German energy transition on coastal communities in Schleswig-Holstein, Germany

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Acknowledgements or credits list:

- Research for this paper was supported through the Cluster of Excellence 'CliSAP' (EXC177), University of Hamburg, which is funded through the German Science Foundation (DFG).

Abstract

Currently, Germany is reshaping its energy sector from fossil fuels to fundamentally relying on renewable energy. Particularly wind energy and bioenergy are of importance to Schleswig-Holstein, the northernmost German federal state. Despite the already considerable development of these sources, further expansion of wind energy and bioenergy production in Schleswig-Holstein can be expected in the next decades, sparked by increased demand in adjacent metropolitan areas and improved energy infrastructure. However, not all communities in the state will equally benefit from this trend. Developing and applying an agent based model of key renewable energy sources in Schleswig-Holstein, we assess the possible (economic) benefits and (environmental) challenges of the energy transition to the coastal communities along the North Sea and Baltic Sea coasts and compare them to the landlocked municipalities. Wind energy and bioenergy have different implications for coastal communities, particularly due to the continued shift of wind energy production from onshore sites to offshore wind farms, increasing the intensity of land use in the affected coastal regions. In contrast, expansion of bioenergy production in coastal communities is much more dependent on energy demand and a successful tradeoff between food and energy because of limited land availability for local agricultural production in Schleswig-Holstein.

Keywords

energy transition, agent based modeling, wind energy, bioenergy, Schleswig-Holstein

1 Introduction

The catastrophic earthquake in Japan in March 2011 that triggered the nuclear meltdown of the plant in Fukushima led to a cascade of consequences that included a drastic change in German energy policy, which included the complete phase-out of nuclear energy by the mid-2020s (Kominek & Scheffran, 2012). In order to achieve this ambitious goal, there has to be a substantial substitution of energy production using renewable sources such as wind energy, solar energy, or bioenergy. Even before the 2011 decision to initiate the energy transition in Germany (“Energiewende”), there had already been a considerable development of renewable energy sources in Germany (Wüstenhagen & Bilharz, 2006). The low-lying flat coastal areas of Northern Germany are particularly suited for energy production from wind but there is considerable intra-state heterogeneity, with wind energy production being most prominent in the coastal counties along the North Sea coast and in Ostholstein near the Baltic Sea (Goetzke & Rave, 2016). Furthermore, large parts of the coastal areas are also used by agriculture, which makes it relatively easy to engage in biomass production for bioenergy plants. Both kinds of energy sources have become increasingly important in the German energy mix since the beginning of the 21st century. Additionally, the potential for energy production from agricultural leftovers such as straw is substantial in Schleswig-Holstein and could become an important alternative to the growth of energy plants in the northernmost German state (Weiser *et al*., 2014).

In contrast to most fossil fuel sources, the renewable sources that are used for energy production in Northern Germany require substantial space: Land that is used to grow energy crops cannot be used for any other purpose simultaneously. While an individual wind turbine does not require a lot of space by itself, there are defined minimum distances between generators that make large wind parks also quite land-intensive endeavors (McKenna *et al*., 2014). This may lead to land use-conflicts as the coastal zones in Northern Germany are usually utilized in multiple ways. Agriculturally used land is generally used to grow food crops or for grazing cattle or sheep on grassland. Furthermore, tourism is an important economic sector in the coastal zones of Schleswig-Holstein (Homp & Schmücker, 2015; Statistikamt Nord, 2016), particularly as the majority of the coastal waters around the German coasts are protected areas or National Parks (Goeldner, 1999; Schiewer, 2008).

Assessments of the possible consequences of changes in land use to fulfill a constantly growing bioenergy production have been conducted for the Eiderstedt peninsula at the West coast of Schleswig-Holstein. Despite the fact that land use in that area has changed over the course of the past centuries (Link & Schleupner, 2007), a quick shift of agricultural land use from grassland to arable farm land to grow large amounts of corn for bioenergy production would have substantial implications for key breeding populations of wading bird species (Schleupner & Link, 2008). Also, tourism is affected to some extent albeit the impacts are much less pronounced (Link & Schleupner, 2011). In addition, it has to be noted that there are substantial disagreements between local farmers and environmental conservationists about land use issues in conjunction with bioenergy production that have not yet been resolved (Schleupner & Link, 2009).

This assessment considers the two most important renewable energy sources in Schleswig-Holstein, wind energy and bioenergy. Applying a newly developed agent-based model, which is based on a corresponding version covering the Jiangsu Province in China (Shu et al., 2015), the development pathways of renewable energy in the northernmost German state are assessed for different scenarios of demand growth. The analysis of consequences for the individual counties focuses on the coastal regions of the state to determine whether there are significant differences in impacts for coastal communities in comparison with the landlocked parts of Schleswig-Holstein. Because of the limited number of land uses in the coastal regions of Northern Germany – the prime focus being agricultural production – it is important to identify and follow sustainable development pathways that successfully increase the adaptive capacity of coastal zones particularly in times of climate change. In the rural parts of Northern Germany, renewable energy can be readily produced due to the given geomorphological setting but its large-scale implementation requires a socio-technological transition to devise land use strategies that simultaneously satisfy the needs for food and energy provision (Geels, 2002) in order to avoid or minimize possible local or regional conflict.

Recent assessments have highlighted the potentials for renewable energy production in Schleswig-Holstein but have also pointed to some conflict risks that need to be considered (Link & Scheffran, 2017; Scheffran et al., 2017). The aim of this study is to assess possible development pathways of renewable energy production in Schleswig-Holstein, Germany, utilizing an agent based model that allows agents to allocate their resources among food, wind energy, or bioenergy production. Simulations are conducted for various levels of subsidies for renewable energy production and results are evaluated for three sub-regions of Germany's northernmost federal state. The following section outlines the current state of renewable energy production in Schleswig-Holstein. Subsequently, the agent-based model used in this assessment is described in detail. Section 4 provides the results of the model simulations for different scenarios of future renewable energy production in Northern Germany. Section 5 discusses the model results and concludes.

2 Renewable energy production in Northern Germany

Northern Germany has already experienced a substantial development of renewable energy sources during the past three decades. In this case study, we focus on the state of Schleswig-Holstein, which lies north of the metropolitan region of Hamburg. Schleswig-Holstein is the northernmost federal state of Germany with an area of almost 16000 km^2 and a population of slightly more than 2.8 million people. It consists of three fundamentally different geomorphological zones: the West of Schleswig-Holstein is very flat marshland with fertile soils, which makes this the prime agricultural area of the state. The central part of Schleswig-Holstein consists of geest with sandy soils, while the East of the state consists of rolling hills and fjords as this part of Schleswig-Holstein has been subject to glaciation during the last ice age (Liedtke & Marcinek, 2002). The overall terrain in Schleswig-Holstein is very flat, the highest elevation being the Bungsberg, which is a mere 168 m above the sea level.

Because of these characteristics, Schleswig-Holstein is the state with one of the best potentials for wind energy production throughout Germany (Ender, 2015). This particularly applies to the western marshlands and the central geest as well as the island of Fehmarn in the Baltic Sea. Outside of Schleswig-Holstein, similarly well-suited areas can only be found in the coastal regions of Lower Saxony and Mecklenburg-West Pomerania. Consequently, wind turbines are primarily located in these preferred zones. Some parts of these areas are already saturated with wind turbines or are already close to being saturated. In other parts of Germany wind energy production is somewhat less pronounced in comparison with other renewable energy sources.

This is reflected by the development of wind energy production in Germany and particularly in Schleswig-Holstein in the past decades. There has been a first sharp increase in wind energy production in the 1990s, with the installed capacity increasing along with the number of installed wind turbines (Ender, 2015). By the turn of the millennium, the installed capacity had exceeded 5000 MW (Bundesministerium für Wirtschaft und Energie, 2017). However, some areas in Germany became saturated with installations since the early 2000s, so a further expansion of wind energy production could only occur by increasing the size of the individual installations. As space for onshore wind energy installations is limited, other options have to be considered in order to maintain the expanding trend of wind energy production in Germany. Consequently, offshore solutions have been sought, mainly in the North Sea area. After a long planning period, the first German offshore wind park has started to produce energy in 2009. At the beginning of 2018, there were nine offshore wind parks in Schleswig-Holstein’s part of the North Sea that were in operation or under construction, totaling 560 individual turbines (Bundesamt für Seeschifffahrt und Hydrographie, 2018). Further offshore wind parks are currently being planned.

Economic benefits from wind energy production have consistently grown since the beginning of the millennium, reaching approximately 1.7 billion Euros in 2015 (Bundesministerium für Wirtschaft und Energie, 2017). Investments have experienced a slight decline as a consequence of the economic crisis in the second half of the 2000s but have soared in recent years to a new high of almost 7 billion Euros for onshore wind turbines and more than 3 billion Euros for offshore wind energy production.

Among the German federal states, Schleswig-Holstein is the leader with regard to wind energy production (Ender, 2015). More than 450 wind turbines were newly installed in Schleswig-Holstein in 2014, which amounts to almost one quarter of all new German wind energy installations. Lower Saxony is a distant second with half as many wind turbines as Schleswig-Holstein. In that year, the installed capacity in Schleswig-Holstein grew by more than 1300 MW, totaling more than 20% of the entire additionally installed capacity of almost 6200 MW. Numerous small installations have been decommissioned recently, making room for larger wind turbines. Repowering has become an important option to replace out-of-date equipment with state-of-the-art technology to secure wind energy production in the upcoming decades. This emphasizes the substantial dynamics in the wind energy sector in Germany.

The geographic distribution of wind turbines in Schleswig-Holstein corresponds well with the wind zones. Wind energy production mainly occurs along the North Sea coast in the counties of Northern Frisia and Dithmarschen (Landesamt für Landwirtschaft Umwelt und ländliche Räume Schleswig-Holstein, 2017) and at the Baltic Sea in the county of Ostholstein, mainly because of the vast amount of turbines on the island of Fehmarn. Some wind parks are also in operation in the western part of Schleswig-Flensburg and in Steinburg near the Elbe River. It has to be noted that wind turbines are generally not evenly distributed throughout the countryside but have been erected in large clusters in areas with particularly favorable conditions. Along the North Sea coast of Schleswig-Holstein, this corresponds to practically all coastal areas that are not protected by the regulations of the Wadden Sea National Park.

The considerable growth of wind energy production in Schleswig-Holstein in the past decades has initially occurred by mainly installing wind turbines on agricultural land so that farmers could harvest energy in addition to their regular crops as individual turbines do not require large amounts of land. This has led to the construction of numerous turbines that have redefined the appearance of the landscape in parts of western Schleswig-Holstein. There is vast potential for wind energy production in the German northernmost state but there are also substantial uncertainties associated with the land use changes occurring in the direct vicinity of the turbines and with local effects of public acceptance (McKenna *et al*., 2014).

However, despite the advantages of wind energy production with regard to emissions reduction, opponents to the continued expansion of renewable energy sources point to the adverse effects of wind turbines: these include noise in the vicinity of the generators (Dai *et al*., 2015), reflections of sunlight from the turbines, killed animals from the rotating hands of the turbines such as birds (Dürr & Langgemach, 2006; Hüppop *et al*., 2006) and bats (Rydell *et al*., 2010), as well as aesthetic reasons (Gee & Burkhard, 2010). Considering that the Wadden Sea and vast parts of the adjacent coastal areas in Schleswig-Holstein are National Parks and of particular ecological value to wildlife, land use conflicts between environmental conservationists and proponents of wind energy production have occurred locally, leading to limitations on the number of wind turbines in the vicinity of protected areas (Gatzert & Kosub, 2016).

To minimize such conflicts, there has been a considerable push to shift the wind energy production in Schleswig-Holstein to offshore sites. However, the construction of offshore sites is associated with substantially higher costs, which also extends to the maintenance of installations and the transport of the generated energy to the consumers who are usually located in considerable distances from the suppliers (Maubach, 2014). Furthermore, there has to be a considerable upgrade in the German power grid to transport the energy from the production sites to Southern Germany and metropolitan areas where demand is greatest (Erlich *et al*., 2006). The future success of wind energy production will rely to a large extent on the development of production costs. Investment costs have to be reduced, particularly as feed-in tariffs are going to be discontinued and wind energy has to compete with other means of energy production on the German market as of 2020 (Nordensvärd & Urban, 2015). In this context, the focus on offshore sites far from the coast may need to be adjusted to sites in closer proximity to the coast as this would reduce construction and operation costs substantially (Maubach, 2014) and offshore production in areas close to the coasts has proven to be a successful alternative in the neighboring countries in the North Sea region. To identify suitable sites, measurable market services of the environment have to be balanced against qualitative, often not clearly tangible, indicators, which are nonetheless equally important. In coastal zones and coastal communities the application of coastal ecosystem service assessments thus seems a feasible approach (c.f. Link & Borchert, 2015).

When looking at renewable energy production in Schleswig-Holstein, wind power is not the only source that is prominent in this mainly rural state of Germany. Also, the production of biogas by fermentation has also expanded substantially in the past decade. First initiatives to promote the production of bioenergy in Schleswig-Holstein were successful even before the turn of the millennium and it took only a few years to install the first significant capacity (Bundesministerium für Wirtschaft und Energie, 2017). In 2001, an equivalent of slightly more than 100 MW was installed, which had increased 40-fold a decade later. Until then, there was a constant expansion in the production of biogas but there has been stagnation in recent years, which may be attributed to changes in the legal boundary conditions regarding the production of renewable energy in Germany. The currently installed capacity of bioenergy production in Schleswig-Holstein is just above 5000 MW.

In contrast to wind energy production, biogas plants are more evenly spaced throughout Schleswig-Holstein, as they are not dependent on any particular physical setting such as favorable wind speeds. Nonetheless, there are far more biogas plants in the North of Schleswig-Holstein – particularly in the counties of Northern Frisia and Schleswig-Flensburg – than in the metropolitan region of Hamburg. This has to do with the fact that biogas plants require a substantial amount of feed-crops that should ideally not have to be transported too far before being processed in the plants. The North of Schleswig-Holstein and the area close to the Danish border is almost entirely used for agricultural production and in this region there is more space for the production of energy crops next to food crops than in the South of the state. Also, most energy crops in Schleswig-Holstein are grown in the Geest area, which roughly corresponds to the central (landlocked) areas of the state. The soils in this part of Schleswig-Holstein are good enough for these crops while the very fertile Marshlands are used more for food crop production.

Similar to wind energy, the increase in the number of biogas plants in Schleswig-Holstein has sparked some serious discussions as there are numerous side effects associated with the production of energy plants for fermentation. Due to its considerable spatial demand, substantial bioenergy production in a given region such as the West coast of Schleswig-Holstein is likely to shape this area as an “energy landscape”, which needs to be managed accordingly in order to avoid land use and public acceptance conflicts (Blaschke *et al*., 2013). A research project has been conducted on the Eiderstedt peninsula at the West coast of Schleswig-Holstein to determine how the landscape has changed due to the continued transformation of grassland to arable farm land to grow corn for biogas production and what the possible implications are for tourism and breeding bird species if the trend of transforming the agricultural land continued (Link & Schleupner, 2007, 2011; Schleupner & Link, 2008, 2009). Depending on the conversion pattern, ecological impacts can vary, despite the fact that the general trends remain similar.

Ecological impacts include adverse effects on breeding bird populations in the area which require sufficient grassland for their breeding success. A substantial conversion of grassland into arable farm land not only decreases the overall amount of land available to the bird populations, it also diminishes the quality of the remaining grassland (Schleupner & Link, 2008). This leads to a disproportionately strong decline in the carrying capacity for several key bird species that can only partly offset this effect by relocating to areas in the vicinity of the peninsula.

Economic impacts of land conversion for energy crop production are harder to quantify. These mainly consist of changes in tourist frequency in the areas of biogas production because of the altered landscape appearance (Link & Schleupner, 2011). Even though tourists are aware of such changes hardly anyone would reconsider their destination choice because of increased energy crop production. Therefore, the economic implications in the region are only marginal. While these local impacts of land use changes, which have been assessed for one particular region in Schleswig-Holstein, point to certain trends, they are by no means indicative of possible developments in other parts of the federal state.

Another critical aspect of renewable energy production in Northern Germany is that a lot of the energy that is produced in Schleswig-Holstein cannot be consumed locally but needs to be transported into adjacent metropolitan regions such as Hamburg where the demand for energy is particularly high. There is also some production of renewable energy in Hamburg but this is by no means sufficient to meet the ever growing demand in the entire metropolitan region (Energymap, 2018; Groscurth, 2005). Therefore, it becomes necessary to transport the energy from the suppliers in the rural areas to the consumers in the urban area. Furthermore, this may cause land use issues in the metropolitan regions as well (Gertz *et al.*, 2015).

Investments into energy transportation infrastructure are a key aspect of the energy transition in Germany. However, it appears to lag behind the expansion of production sites of renewable energy (Erlich et al., 2006) and efforts have to increase to make the energy transition a successful endeavor in the long run (Scholz *et al.*, 2014). Critics of the strong emphasis on renewable energy stress this point as well as the fact that the public acceptance of large energy transportation projects is also limited (Bertsch *et al.*, 2016). Nonetheless, efforts to install adequate capacities to transport energy from its sources to the areas of demand are well under way and should be able to bridge this gap in upcoming years (Beveridge & Kern, 2013).

As Schleswig-Holstein is a key provider of renewable energy in Germany, it is important to determine what potentials can actually be realized for different political and economic boundary conditions and how such developments affect land use in the rural parts of the state where the energy is mostly produced – particularly in the coastal regions. This is done using an agent-based model that simulates possible developments of renewable energy production in Schleswig-Holstein with a particular focus on the two main renewable energy types: wind and bioenergy. The model output consists of possible development pathways of agricultural and energy production until the middle of the 21st century for various sets of constraints. The feasibility and resulting conflict potentials of these development trajectories can then be analyzed with sudden substantial land use changes pointing to possible sources of conflict.

3 The dynamic agent-based model

The agent-based model of renewable energy production in Schleswig-Holstein simulates the annual decisions of farmers with regard to intensity and type of crop production in order to meet the demands for both food crops and energy biomass. Furthermore, the farmers have the option to invest in the construction of wind turbines on their property to supplement income from agricultural production by producing electricity from wind.

3.1 Model framework

The model combines a dynamic agent-based model and a partial equilibrium model of agriculture in Schleswig-Holstein (Figure 1). The geographical characteristics of the individual agents are maintained in the model by using a spatial grid that positions the agents in the landscape. This way, it is possible to distinguish agents in coastal regions from those in landlocked parts of Schleswig-Holstein. The agents are aggregated to three regions, where the communities adjacent to the North Sea or Baltic Sea are divided into two coastal regions and the remaining landlocked part of the state is considered as a third agent. The distinction between the North Sea coast and the Baltic Sea coast is made because of the different geomorphological settings of the two coastal areas, which leads to different renewable energy production patterns in these regions.

In the agricultural sector model, all farmers of one of the regions distinguished in the model are considered as one agent. This part of the agent-based model is adapted from the Agricultural Sector and Mitigation of Greenhouse Gases (ASMGHG) model (Schneider & McCarl, 2003), which relates local cropping systems to agricultural commodity markets. The model also relates each agent’s agricultural production scheme to the local bioenergy and wind energy markets. This way, the dynamic agent-based model can effectively consider the local geographic characteristics of each agent in the context of the given boundary conditions related to energy crop production. By relating biomass supply from all farmers to bioenergy production goals, the decisions of all agents in the market become interlinked. Similarly, decisions on wind energy production are based on the respective development goals for the energy type. Note that all production goals are based on political decisions and are thus in reality subject to substantial possible change if an administration chooses to regionally change the course of the energy transition that was set by its predecessor.

INSERT FIGURE 1 HERE

Figure 1: The framework of the dynamic agent-based model of optimized energy landscapes in Schleswig-Holstein (adapted from Shu *et al*., 2015).

3.2 Model Structure

The model applied in this assessment determines the most cost-efficient land use pattern that not only meets the regional remand for food but also addresses the demand for biomass for bioenergy production. Production of wind energy is considered separately as the unit area requirement of an individual wind turbine is rather limited in comparison to the space requirement of agricultural land for energy plants. The model is programmed in GAMS and consists of an objective function, a group of decision variables, and a set of constraints.

INSERT FIGURE 2 HERE

Figure 2: Implementation of the framework in the dynamic agent-based model.

Farmers can plant crops that will either be used as food or as input to bioenergy production (Figure 2). Furthermore, farmers can invest into wind turbines that will be constructed on their property to produce electricity from wind. Decisions regarding which crops to plant for which purpose and whether to invest in wind energy production depend on the developments of the energy market and the market for agricultural goods. Therefore, the decisions of an individual agent, i.e. one region of the state, have an influence on the entire sector and subsequently on the other agents as well.

The objective function maximizes the net present value of profits from agriculture and energy production over the 37-year time horizon of the simulation (2013 to 2050). Decisions are determined on an annual basis, adhering to the constraints that are based on environmental limits and economic demand for agricultural goods. Mathematically, these constraints define the convex feasible region[i] for all decision variables and are described in greater detail in the appendix.

In the simulations, an optimization is performed for each time step to obtain the best possible set of values for the variables that not only are consistent with all the constraints but also maximize the objective function. In economic terms, this maximum of the objective function is referred to as competitive market equilibrium (McCarl & Spreen, 1980). In addition to the production allocation in each region, the energy and crop yields for each time step as well as the associated market prices for the given set of political, economic, and technological boundary conditions can be determined.

3.3 Model parameterization and scenarios

In this assessment, the model is applied to simulate the possible development of bioenergy and wind energy production in Schleswig-Holstein from present until the middle of the 21st century. Regionally, the model distinguishes between the North Sea coastal area, landlocked Schleswig-Holstein, and the Baltic Sea coastal area. These three areas have different characteristics with regard to suitability as locations for wind turbines with the North Sea coastal area being more suitable for wind energy production than the other regions. In contrast, the landlocked part of Schleswig-Holstein is slightly favored for bioenergy production as Geest soils are somewhat disadvantaged in comparison to e.g. the rich Marshland soils with regard to food crop production, leaving this region as a prime candidate area for energy crop production. These relative advantages are included in the model as increased energy output per unit area.

All scenarios analyzed are based on the fundamental goal of reducing carbon dioxide emissions in Schleswig-Holstein by 40% by the year 2020 and by more than 80% by the middle of the 21st century in comparison to 1990 (Ministerium für Inneres und Bundesangelegenheiten des Landes Schleswig-Holstein, 2017). This corresponds to a necessary increase of renewable energy production to 37 TWh in 2025 for Schleswig-Holstein and a goal for 2050 that is accordingly higher. This drives the investments into additional wind turbines and more bioenergy production. A sensitivity analysis is conducted with regard to the level of subsidies granted to renewable energy production. At the onset of the energy transition in Germany, investments into the construction of renewable energy infrastructure were highly subsidized by the government. In recent years, the desire to continue such subsidies has decreased considerably and it remains to be seen whether they might disappear entirely. At current levels of subsidies or without subsidies at all, investment decisions follow the same pattern. This is referred to as the reference case. To qualitatively alter development pathways, considerably higher subsidies would be necessary. A first fundamental shift in production patterns occurs if subsidies reach a level of approximately seven times the current subsidies (medium subsidy case). Another occurs if subsidies exceed ten times the current level (high subsidy case). These possible development pathways of renewable energy production in Schleswig-Holstein are assessed in the subsequent sensitivity analysis. A special emphasis is placed on the coastal areas along the North Sea and the Baltic Sea to see whether some parts of the state are particularly useful for renewable energy production.

Simulations are conducted for the time period 2013-2050. The initial values of the parameters and decision variables (Table 2 and Table 3) are based on official statistical data provided by the *Statistisches Amt für Hamburg und Schleswig-Holstein*.

4 Simulation results

As an exemplary application of the model, a sensitivity analysis is conducted that shows how renewable energy production in Schleswig-Holstein is affected by different levels of subsidies. These vary from zero, which is a possibility if changes in state policy lead to altered energy feed-in regulations, to ten times the current level.

INSERT FIGURE 3 HERE

Figure 3: Selected results of the simulation model: a) agricultural land devoted to food crop production; b) agricultural land devoted to energy crop production; c) number of bioenergy plants; d) number of wind turbines.

Subsidies granted for renewable energy production in Germany are currently at a level that does not have a profound impact on agricultural land use. If subsidies remain at present rates or vary only slightly, there is practically no effect on agricultural land use patterns (Figure 3a). The amount of land devoted to food crop production remains constant in total and there are only marginal shifts in the kind of crops produced. Right now, bioenergy plants predominantly use corn as fuel crops while energy crops such as switchgrass, different kinds of reed, and miscanthus are only of comparably low importance (Figure 3b).

However, this would change if subsidies for renewable energy production increased by a factor of more than 5. In that case, agricultural production patterns shift substantially from food production to the growth of perennial energy plants. Approximately one third of the arable farm land that is mainly used to produce wheat (Figure 3a) is reallocated to mostly grow reed. This shift affects agricultural land in all regions of Schleswig-Holstein, so the relative change is distributed fairly evenly between coastal and landlocked parts of the state (Figure 3b).

This shift in agricultural production patterns is reflected in the development of the number of bioenergy plants in Schleswig-Holstein. For current subsidies of renewable energy production, there is only a marginal increase in the number of bioenergy plants in the future (Figure 3c). If subsidies are discontinued altogether, the number of plants does not increase at all anymore. In contrast, if the production of special energy plants is substantially intensified, this coincides with a pronounced increase in the number of plants as well. These are distributed fairly evenly geographically, so that there is no magnified impact on the coastal regions of Schleswig-Holstein. Based on the model, a substantial further expansion of bioenergy production is only possible with adequate financial incentives.

The situation is somewhat different for wind energy production. There is a continued increase in the number of wind turbines in Schleswig-Holstein in all scenarios (Figure 3d). As expected the growth in the wind energy sector is most pronounced if the financial incentives are higher but there are some limits to the expansion due to the substantial investment costs involved. Also, the current concentration of wind energy production along the North Sea coast has the effect that the future expansion is somewhat inhibited, which is most likely a consequence of the minimum distance constraint. This does not affect the other regions of Schleswig-Holstein, so their relative importance in wind energy production increases despite the fact that these regions have a somewhat smaller wind potential.

5 Discussion and conclusion

The results of the simulation model indicate that renewable energy production will continue to play a fundamental role in Schleswig-Holstein and in particular in its coastal regions. In most of the scenarios the share of renewable energy production continues to grow, although it takes a considerable effort to achieve the goals set by the administration of Schleswig-Holstein.

A substantial increase in renewable energy production has implications on land use in the long run. In the scenarios with high subsidies for bioenergy, agricultural production shifts from conventional food crops to energy crops. That the shift is of similar magnitude in all parts of the state indicates that for bioenergy there is no significant difference between coastal areas and the landlocked parts of Schleswig-Holstein. Interestingly, there is practically no increase in energy crop growth over time if there are little or no subsidies for bioenergy production. This corresponds well with the recent development in Schleswig-Holstein that saw practically no new plants for bioenergy production being built during the past couple of years. New facilities require considerable investments and there appears to be little economic potential for further expansion of bioenergy production in Schleswig-Holstein should the current boundary conditions persist.

On the other hand, wind energy still has the potential to expand. However, there is a saturation effect with regard to wind energy in the coastal areas near the North Sea while there is continued expansion in the other parts of the state. Wind turbines are already quite prevalent in this part of Schleswig-Holstein and the model does not allow the number of wind turbines to exceed a predefined limit in the coastal region of the North Sea, which is based on current regulation and the fact that substantial areas of the North Sea coast are protected by the National Park “Wadden Sea of Schleswig-Holstein”. Without this constraint, the optimal model solution would be to produce all the desired renewable energy from wind turbines in the North Sea coastal area, a result that is unrealistic under current regulation and because of the associated adverse environmental impacts on biodiversity as well as public opposition. This model version considers only on-shore wind energy production. An inclusion of possible offshore wind parks would avoid this effect and open up additional potential for wind energy production.

An expansion of renewable energy production based on economic considerations will affect all parts of the state to some extent. While impacts from installations of new bioenergy plants are similar for both coastal and the landlocked regions of Schleswig-Holstein, implications of an increased number of wind turbines should be less pronounced along the North Sea coast as the expansion would mainly affect the other regions of the state. However, it has to be noted that the model does not consider local opposition to renewable energy projects, which could locally decrease the profitability of renewable energy production if increased costs to address concerns of local interest groups were to be included.

While the given model version already yields some useful insights into the possible development pathways of renewable energy in Schleswig-Holstein, further model development is advisable with respect to various aspects. First of all, the spatial resolution should be increased from three regions to county level as it would be then possible to capture the effects of varying regulation concerning renewable energy production between counties. Furthermore, agricultural production patterns (i.e. the decision whether food or energy crops are planted) are based on a continuation of current trends in market prices for the different commodities. While this is a reasonable assumption to start with, sudden and unexpected developments on food and energy crop markets can have profound impacts that are also worth studying. Finally, energy demand and supply are currently considered in the model only for Schleswig-Holstein in isolation. However, the energy transition in Germany can only be successful if sufficient infrastructure is established to transport the vast amounts of energy generated in the mostly rural areas – such as Schleswig-Holstein – to the mostly urban areas, in which energy demand is greatest. In case of Schleswig-Holstein this would be the adjacent metropolitan area of Hamburg but also connections to areas in Denmark appear reasonable. The nature and extent of such relationships should also be assessed in model simulations.

Nonetheless, it is already possible to analyze potential pathways of renewable energy production in Schleswig-Holstein for different economic and regulatory boundary conditions. The continued expansion of renewable energies in the German northernmost state is necessary if the desired production goals set by the state administration are to be reached. And whether it is wind or bioenergy that is reaped in Schleswig-Holstein, within the German context the overall success of the energy transition is considerably dependent on the amount of renewables produced in the state between the North Sea and the Baltic Sea. Furthermore, the energy transition provides a substantial opportunity for a socio-technological transition predominantly in the coastal areas, in which so far land use has been generally limited to agriculture, nature conservation, and tourism. Renewable energy production may considerably increase the economic importance of these previously relatively disadvantaged regions. It is important to identify sustainable development pathways that minimize conflict potential between energy and food production and other associated land uses.

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7 Appendix: Detailed dynamic agent-based model specifications

The general formulation of the regional dynamic agent-based model, which is based on the model of renewable energy production in a Chinese province (Shu et al., 2015) maximizes the present value of the total profits across the entire simulation period of a system that considers both wind energy and bioenergy production. With regard to bioenergy, it covers the cultivation of both conventional crops and energy crops, subject to resource endowment constraints, energy crop transition constraints, cultivation selection constraints, and product demand constraints. With respect to wind energy, it determines how many wind turbines should be installed for the given constraints on allowed wind turbine density and wind potential.

7.1 Indices

Table 1: Model indices

index	Description
r	regions
allcrop	all crops
fc	conventional food crops
ec	energy crops
pr	agricultural products
grains	grains
biomass	bioenergy feedstock
time	time horizon
ht	historical year
t	simulation year
s	policy scenario
a	crop age
l	biomass-based power plant locations
j	wind farm locations
number	the order of construction of wind turbines at a given location
bio-device	type of biomass-based power generation turbine
wind-device	type of wind power generation turbine

7.2 Parameters

Table 2: Model parameters

parameter name	Description
$y_{t,r,fc,pr}^{conventional\,crop}$	yield of conventional crop (t/ ha)
$y_{ec,biomass,a}^{energy\,crop}$	yield of perennial crop (t/ ha)
$ps_{t,pr,s}$	price subsidy (EUR/ t)
$v_{pt,biomass}$	price of *biomass* in year *t* (EUR/t)
$sub_{t,r,fc,s}^{conventional\,crop}$	land subsidy for conventional crops (EUR/ha)
$sub_{t,r,ec,s}^{energy\,crop}$	land subsidy for perennial crops (EUR/ha)
$b_{t,r}^{land}$	total arable land area (ha)

$h_{ht,r,fc}$	historical cultivation area (ha)
k_{ec}	expected lifespan of energy crops (year)
$dema_{t,grains}^{grains}$	demand of grains (t)
discount	discount rate
$\eta_{t}^{biomass}$	share of straw used for energy production in relation to its total amount (%)
$\alpha^{biomass}$	ratio of straw from main conventional crops to local biomass potential (%)
$c_{t,r,fc}^{conventional\,crop}$	plantation cost of conventional crops *fc* in region *r* year *t* (EUR/ha)
$c_{t,r,ec,a}^{energy\,crop}$	plantation cost of energy crops *pc* at age of *a* in region *r* year *t* (EUR/ha)
$c_{biomass,t}$	transportation costs per unit amount and distance in year *t* (EUR/km)
k_{device}	life span of fixed equipment in power plant (years)
dem_{t}^{power}	demand of electricity in year *t* (kwh)
$d_{r,j}$	distance between one location *r* and another location *j* (km)
$b_{t}^{biopower}$	annual fixed investment cost for biomass-based power plant in year *t* (EUR/MW)
$o_{t}^{biopower}$	other operational costs for biomass-based power plant in year *t* (EUR/MW)
$v_{t}^{biopower}$	fuel cost for electricity generation from biomass-based power plant in year *t* (EUR/MW)
$i^{\max,biopower}$	maximum capacity of biomass-based power plant in practice (MW)
$\alpha^{biopower}$	conversion factor from biomass to bioelectricity (kwh/t)
$\eta^{biopower}$	efficiency of bioelectricity generation (no unit)
$\sigma^{biopower,max}$	maximum annual utilization hours of biomass-based power plant (hours)
$\widehat{i}_{l,t}$	newly added capacity of the existing biomass-based power plant built at location *l*, year *t* (MW)
$cap_{device}^{biopower}$	unit capacity of each type of biomass-based power generation turbine (MW)
$b_{t}^{windpower}$	annual fixed investment cost for wind farms in year *t* (EUR/MW)
$o_{t}^{windpower}$	other operational costs for wind farms in year *t* (EUR/MW)
$i^{\max,windpower}$	maximum capacity of wind farms in practice (MW)
$\eta^{windpower}$	efficiency of wind power generation (unitless)
$\sigma^{windpower,max}$	maximum annual utilization of wind farms (hours)
$\widehat{i}_{j,t}$	newly added capacity of the existing wind farms built at location *j*, year *t* (MW)
$cap_{device}^{windpower}$	unit capacity of each type of wind turbine (MW)
$\rho_{j,t}$	pre-defined density of wind farms in region *j* year *t*

7.3 Decision variables

Table 3: Model variables

variable name	Description	variable type
$PRICE_t^{grains}$	price of grains (EUR/t)	non-negative
$PRICE_t^{power}$	price of electricity (EUR/kwh)	non-negative
$LAND_{t,r,fc}^{conventional\,crop}$	cultivated area for food crops (10^3 ha)	non-negative
$LAND_{t,r,ec,a}^{energy\,crop}$	cultivated area for perennial crops on arable farm land (10^3 ha)	non-negative
$CMIX_{t,r,ht}$	weighting coefficient of historical data	non-negative
$Y_{r,l,t}^{biomass}$	amount of biomass shipped from biomass production location *r* to biomass-based power plant at location *l* in year *t* (t)	non-negative
$Y_{l,number,t}^{biopower}$	amount of electricity generated by the *number*th biomass-based power plant located at *l* in year *t* (kwh)	non-negative
$\widehat{Y_{l,t}^{biopower}}$	amount of electricity generated by the biomass-based power plant located at *l* in year *t* (kwh)	non-negative
$Y_{j,number,t}^{windpower}$	amount of electricity generated from the *number*th wind farm located at *l* in year *t* (kwh)	non-negative
$\widehat{Y_{j,t}^{windpower}}$	amount of electricity generated by the wind farm located at *j* in year *t* (kwh)	non-negative
$I_{i,number,bio-device,t}$	number of new turbines of capacity *device* in the *number*th biomass-based power plant built at location *l* in year *t*	integer
$I_{j,number,wind-device,t}$	number of new turbines of capacity *device* in the *number*th wind farm built at location *j* in year *t*	integer

7.4 Objective function

Max WELF =

$$
\begin{aligned}
&\sum_{t}(1+discount)^{t}\cdot \\
&\left\{
\begin{aligned}
&\sum_{r,\,fc,grains}\left[y_{t,r,\,fc,grains}^{conventional\,crop}\cdot LAND_{t,r,\,fc}^{conventional\,crop}\cdot\left(PRICE_{t}^{grains}+ps_{t,grains,s}\right)\right]\\
&+\sum_{r,\,fc}[LAND_{t,r,\,fc}^{conventional\,crop}\cdot sub_{t,r,\,fc,s}^{conventional\,crop}]\\
&+\sum_{r,ec,a}\left[LAND_{t,r,ec,a}^{energy\ crop}\cdot sub_{t,r,ec,s}^{energy\,crop}\right]\\
&+\sum_{t}\left[(PRICE_{t}^{power}+ps_{t,s}^{biopower})\cdot\left(\sum_{l,number}Y_{l,number,t}^{biopower}+\sum_{l}\widehat{Y_{l,t}^{biopower}}\right)\right]\\
&+\sum_{t}\left[(PRICE_{t}^{power}+ps_{t,s}^{windpower})\cdot\left(\sum_{j,number}Y_{j,number,t}^{windpower}+\sum_{j}\widehat{Y_{j,t}^{windpower}}\right)\right]
\end{aligned}
\right\}\\
&-\sum_{t}(1+discount)^{t}\cdot\\
&\left\{
\begin{aligned}
&\sum_{r,\,fc}\left[c_{t,r,\,fc}^{conventional\,crop}\cdot LAND_{t,r,\,fc}^{conventional\,crop}\right]\\
&+\sum_{r,ec,a}\left[c_{t,r,ec,a}^{energy\,crop}\cdot LAND_{t,r,ec,a}^{energy\,crop}\right]\\
&+\sum_{r,l}\left(c_{biomass,t}\cdot d_{r,l}\cdot Y_{r,l,t}^{biomass}\right)\\
&+\sum_{l,number}\left[(b_{t}^{biopower}+o_{t}^{biopower})\cdot\sum_{device,t1\in t-14\to t}\left(I_{l,number,device,t1}\cdot cap_{device}^{biopower}\right)+v_{t}^{biopower}\cdot Y_{l,number,t}^{biopower}\right]\\
&+\sum_{l}\left(o_{t}^{biopower}\cdot\sum_{t1\in allt-14\to t}\widehat{i_{l,t1}}+v_{t}^{biopower}\cdot\widehat{Y_{l,t}^{biopower}}\right)\\
&+\sum_{j,number}\left[(b_{t}^{windpower}+o_{t}^{windpower})\cdot\sum_{device,t1\in t-14\to t}\left(I_{j,number,device,t1}\cdot cap_{device}^{windpower}\right)+v_{t}^{windpower}\cdot Y_{j,number,t}^{windpower}\right]\\
&+\sum_{j}\left(o_{t}^{windpower}\cdot\sum_{t1\in allt-14\to t}\widehat{i_{j,t1}}+v_{t}^{windpower}\cdot\widehat{Y_{j,t}^{windpower}}\right)
\end{aligned}
\right\}\\
&\forall s
\end{aligned}
\tag{1}
$$

The objective function (1) of the model maximizes the net present value of cash flows of the renewable energy sector in Schleswig-Holstein over the entire simulation period. The revenues consist of the sale of agricultural products, energy, governmental subsidies, and terminal values[1]. The costs are mainly related to land resources, labor resources, fertilizers, pesticides, and other auxiliary inputs.

The revenue terms account for:

- the sales revenue from conventional food crops
- the subsidy for conventional crops
- the subsidy for energy crops
- the sales revenue from electricity generated from energy crops
- the sales revenue from electricity generated from wind turbines

The cost items are:

- the cost of production inputs for conventional crops
- the cost of production inputs for energy crops
- investments in the construction of bioenergy plants
- investments in the construction of wind turbines

7.5 Constraints

7.5.1 Land endowment constraint

The most fundamental physical constraint on crop cultivation arises from the use of scarce and immobile resources. Particularly, the use of agricultural land is limited by given regional endowments of arable land. In equation (2), *b* denotes total arable land area in region *r* in year *t*.

$$\sum_{fc} LAND_{t,r,fc}^{conventional\,crop} + \sum_{ec,a} LAND_{t,r,ec,a}^{energy\,crop} \leq b_{t,r}^{land} \qquad \forall t,r \qquad (2)$$

Equation (2) requires the sum of the arable farm land allocated to particular types of crops, which includes conventional and energy crops, to be smaller than the amount of locally accessible arable farm land during a given season; no matter which kind of field management has been adopted. This, to some extent, reflects the possible land use conflict between food crops and energy crop production.

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[1] Terminal values are estimated for each crop. For energy crops, it is calculated as the net present value of future profits for the remaining productive life of the cultivation: $PV = \sum_t (\mathrm{P}_t \cdot \mathrm{Y}_t - PC_t) \cdot (1+\mathrm{r})^{-t}$, where P_t is the price of the crop in period *t*, Y_t is the yield, and PC_t is the production cost.

7.5.2 Energy crop consistency constraint

Equation (3) focuses on energy crop consistency. Considering its natural death or the farmers' active eradication, the plantation area of perennial energy crops can never be larger but only smaller than or equal to their area in the prior year.

$$-LAND_{t-1,r,ec,a-1}^{energy\,crop} + LAND_{t,r,ec,a}^{energy\,crop} \le 0 \Big|_{1<a\le k_{ec}} \qquad \forall t,r,ec,a \tag{3}$$

7.5.3 Crop mix constraint

This constraint addresses aggregation related aspects of farmers' decisions. Equation (4) forces farmers' cropping activities *LAND* either in summer or in autumn to fall within a convex combination of historically observed seasonal choices *h*. Based on decomposition and economic duality theory, Önal and McCarl (1991) show that historical crop mixes represent rational choices embodying numerous farm resource constraints, crop rotation considerations, perceived risk reactions, and a variety of natural conditions. In equation (4), the *h* coefficient contains the observed crop mix levels for the historical years. *CMIX* are positive, endogenous variables indexed by historical year and region whose level is during the optimization process.

$$-\sum_{ht}\left(h_{ht,r,fc} \cdot CMIX_{t,r,ht}\right) + LAND_{t,r,fc}^{conventional\,crop} = 0 \quad \forall t,r,fc \tag{4}$$

However, crop mix constraints are not applied to the crops, which under certain policy scenarios can be expected to expand far beyond the upper bound of historical relative shares (Schneider *et al.*, 2007). As the cultivation area of energy crops is expected to increase in the future, these crops are naturally excluded from this equation.

7.5.4 Food security constraint

This constraint defines the satisfaction of the requirement of food security in the context of expanding bioenergy production. The first term of equation (5) denotes the demand of a given food crop, the following terms denote the produced food from conventional crops.

$$dema_{t,grains}^{grains} - \sum_{r,fc}\left(y_{t,r,fc,grains}^{conventional\,crop} \cdot LAND_{t,r,fc}^{conventional\,crop}\right) \le 0 \qquad \forall t, grains \tag{5}$$

7.5.5 Biomass demand-supply constraint

This constraint deals with the amount of biomass that is available for energy production. Equation (6) provides that the biomass amount used for energy production cannot exceed the total biomass produced by the agricultural sector in a given time period.

$$\sum_{l} Y^{biomass}_{r,l.t} - \sum_{fc,biomass} \eta_t \cdot \frac{y^{conventional\,crop}_{t,r,fc,biomass} \cdot LAND^{conventional\,crop}_{t,r,fc}}{\alpha} - \sum_{ec,biomass,a} y^{energy\,crop}_{t,r,ec,biomass,a} \cdot LAND^{energy\,crop}_{t,r,ec,a} \leq 0$$

$$\forall r,t \qquad (6)$$

7.5.6 Electricity demand constraint

This constraint addresses the demand for renewable energy. Equation (7) requires the produced electricity from wind turbines and from bioenergy plants to at least match the associated energy demand in a given time period.

$$\sum_{l,number} Y^{biopower}_{l,number,t} + \sum_{l} \widehat{Y^{biopower}_{l,t}} + \sum_{j,number} Y^{windpower}_{j,number,t} + \sum_{j} \widehat{Y^{windpower}_{j,t}} \geq dem^{power}_{t} \qquad \forall t \qquad (7)$$

7.5.7 Total investment constraint

This constraint limits the amount of investments that can be made in a given time period into the expansion of renewable energy production. Equation (8) not only considers the capital costs for the installation of new energy infrastructure but also includes the regularly occurring operation costs.

$$(1+discount)^{t}\cdot\left\{\begin{array}{l}\sum_{r,fc}\left[c_{t,r,fc}^{conventional\ crop}\cdot LAND_{t,r,fc}^{conventional\ crop}\right]\\ +\sum_{r,ec,a}\left[c_{t,r,ec,a}^{energy\,crop}\cdot LAND_{t,r,ec,a}^{energy\,crop}\right]\\ +\sum_{r,l}\left(c_{biomass,t}\cdot d_{r,l}\cdot Y_{r,l,t}^{feedstock}\right)\\ +\sum_{l,number}\left[(b_{t}^{biopower}+o_{t}^{biopower})\cdot\sum_{device,t1\in t-14\rightarrow t}\left(I_{l,number,device,t1}\cdot cap_{device}^{biopower}\right)+v_{t}^{biopower}\cdot Y_{l,number,t}^{biopower}\right]\\ +\sum_{l}\left(o_{t}^{biopower}\cdot\sum_{t1\in allt-14\rightarrow t}\widehat{i_{l,t1}}+v_{t}^{biopower}\cdot\widehat{Y_{l,t}^{biopower}}\right)\\ +\sum_{j,number}\left[(b_{t}^{windpower}+o_{t}^{windpower})\cdot\sum_{device,t1\in t-14\rightarrow t}\left(I_{j,number,device,t1}\cdot cap_{device}^{windpower}\right)+v_{t}^{windpower}\cdot Y_{j,number,t}^{windpower}\right]\\ +\sum_{j}\left(o_{t}^{windpower}\cdot\sum_{t1\in allt-14\rightarrow t}\widehat{i_{j,t1}}+v_{t}^{windpower}\cdot\widehat{Y_{j,t}^{windpower}}\right)\end{array}\right\}\leq Invest_{t}$$

$$\forall t \qquad (8)$$

7.5.8 Density of wind farms constraint

According to German regulation, there must be a defined minimum distance between two wind turbines. This distance is set to avoid adverse effects of one wind turbine on adjacent turbines via effects on local wind patterns. Equation (9) determines whether the installation of a wind turbine is possible in a given location depending on the location of already existing wind turbines.

$$I_{j,number,t1}=\left\{\begin{array}{ll}0, & when \sum_{wind-device} I_{j,number,wind-device,t1}=0\\ 1, & else\end{array}\right\}$$

$$\sum_{number,t1\in t-14} I_{j,number,t1}+\sum_{t1\in allt-14\rightarrow t}\widehat{i_{j,t1}}\leq\rho_{j,t1} \qquad \forall j,t \qquad (9)$$

7.5.9 Set of constraints concerning biomass-based power energy generation

These constraints govern the transformation process from biomass to bioelectricity. Equation (10) denotes how much bioenergy can be generated from a given amount of biomass. The conversion rate depends on the kind of biomass that is used for energy generation. Equation (11) limits the amount of bioenergy that can be generated in a particular power plant in any given period of time. Equation (12) recognizes that a given power plant cannot be operated all year round. The amount of energy generated depends on a plant's capacity and the maximum time of operation.

7.5.9.1 Bioenergy conversion constraint

$$\sum_{number} Y^{biopower}_{l,number,t} + \widehat{Y^{biopower}_{l,t}} \le \sum_{r} Y^{biomass}_{r,l,t} \cdot \alpha^{biopower} \cdot \eta^{biopower} \qquad \forall l,t \tag{10}$$

7.5.9.2 Biomass-based power plant capacity limitation

$$\sum_{device,t1 \in t-14 \to t} I_{l,number,device,t1} \cdot cap^{biopower}_{device} \le i^{\max,biopower} \qquad \forall l, number, t \tag{11}$$

7.5.9.3 Bioenergy generation constraint

$$Y^{biopower}_{l,number,t} \le \sigma^{biopower,max} \cdot \sum_{t1 \in device, t-14 \to t} \left(I_{l,number,device,t1} \cdot cap^{biopower}_{device} \right) \qquad \forall l, number, t \tag{12}$$

7.5.10 Set of constraints concerning wind power generation

Similar to bioenergy production, these constraints govern the energy generation process from wind. Equation (13) denotes how much wind energy can be generated from a given wind potential. The conversion rate also depends on the efficiency of the given wind turbine. Equation (14) limits the amount of wind energy that can be generated by a particular wind turbine in any given period of time. Equation (15) recognizes that a given wind turbine cannot be operated all year round. The amount of energy generated depends on the turbine’s capacity and the maximum time of operation.

7.5.10.1 Wind energy conversion constraint

$$\sum_{number} Y^{windpower}_{j,number,t} + \widehat{Y^{windpower}_{l,t}} \le Y^{windpotential}_{j,t} \cdot \alpha^{windpower} \cdot \eta^{windpower} \qquad \forall j,t \tag{13}$$

7.5.10.2 Wind farm capacity constraint

$$\sum_{device,t1 \in t-14 \to t} I_{j,number,device,t1} \cdot cap^{windpower}_{device} \le i^{\max,windpower} \qquad \forall j, number, t \tag{14}$$

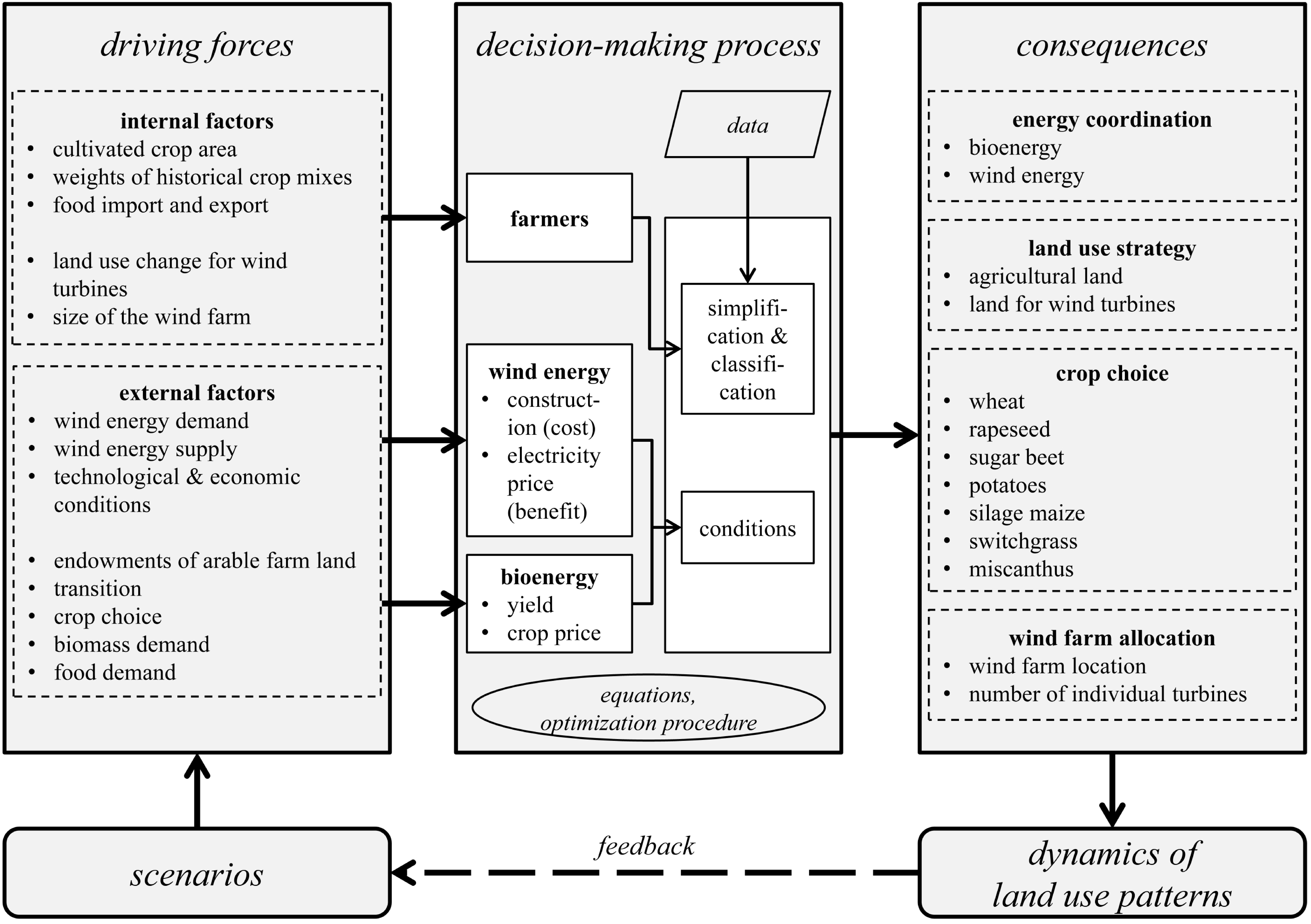
7.5.10.3 Wind energy generation constraint

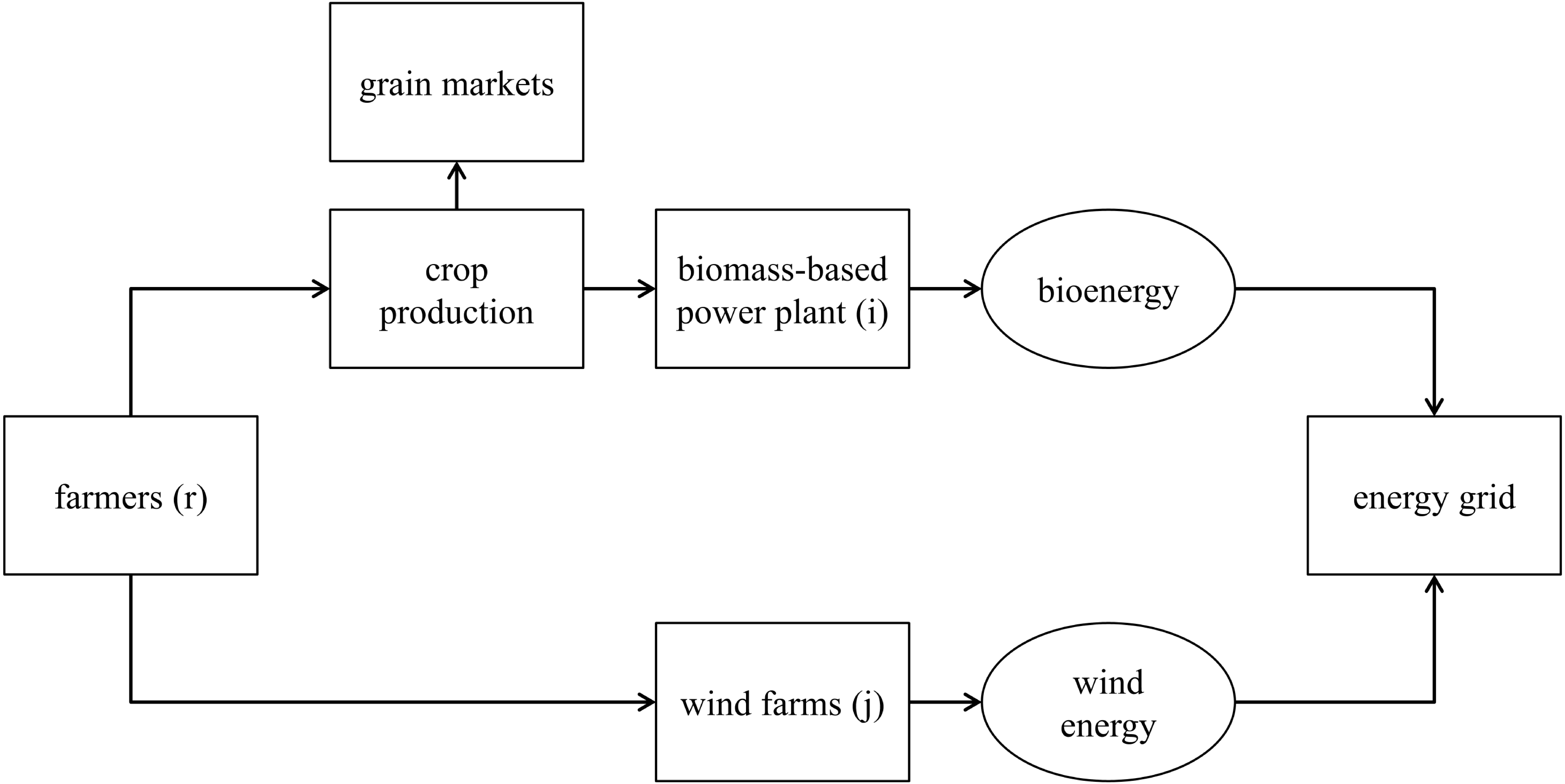
$$Y^{windpower}_{j,number,t} \le \sigma^{windpower,max} \cdot \sum_{t1 \in device, t-14 \to t} \left(I_{j,number,device,t1} \cdot cap^{windpower}_{device} \right) \qquad \forall j, number, t \tag{15}$$

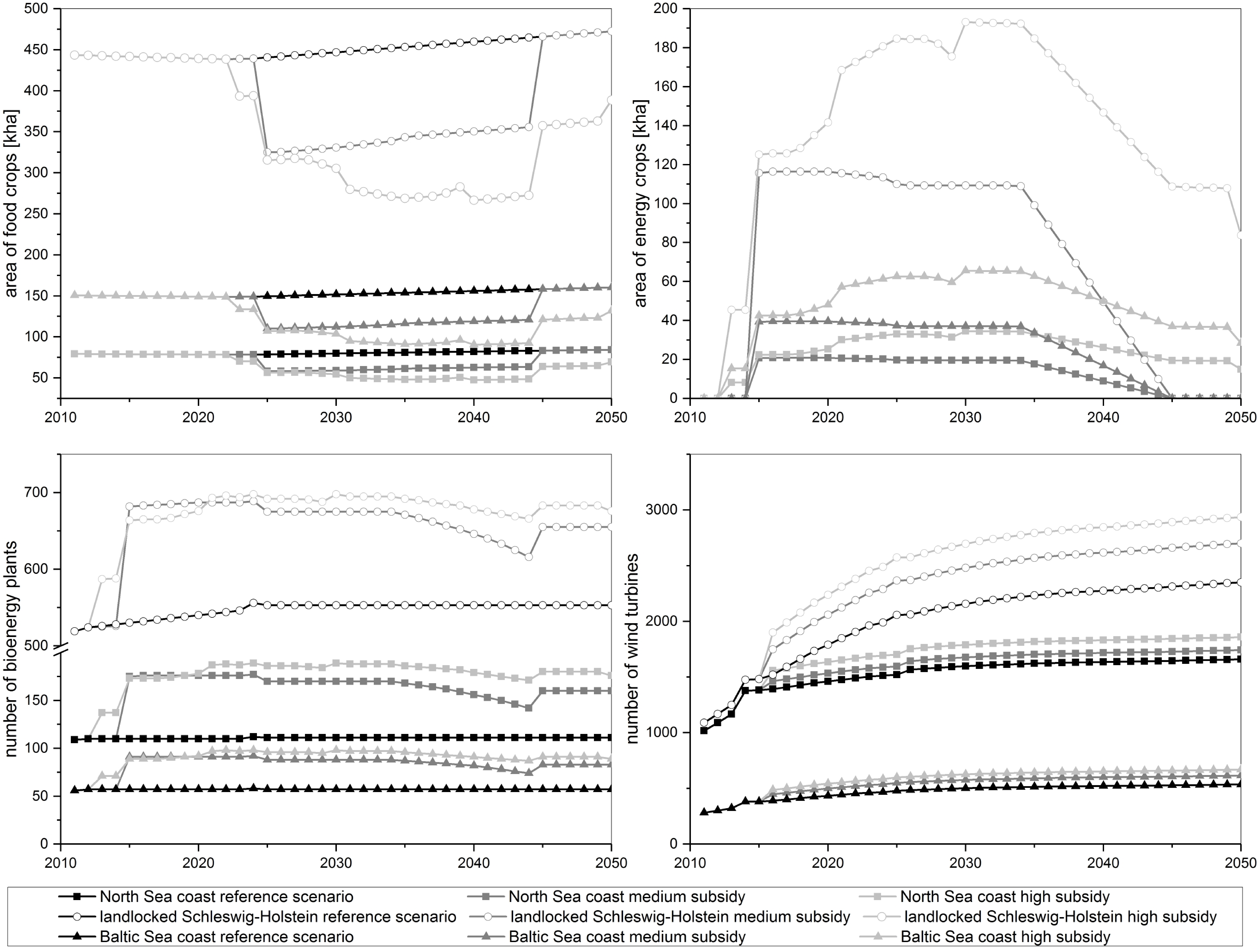
---

[i] In mathematical optimization, a feasible region is the solution space of all possible solutions of an optimization problem that satisfy the problem's constraints. It can be considered to be the initial set of candidate solutions to the problem prior to the start of the optimization.

If the feasible region is convex, i.e. line segments connecting any two feasible points only go through other feasible points, this helps the optimization process as any local maximum that is determined simultaneously is a global maximum as well.


driving forces
internal factors
• cultivated crop area
• weights of historical crop mixes
• food import and export
• land use change for wind turbines
• size of the wind farm
external factors
• wind energy demand
• wind energy supply
• technological & economic conditions
• endowments of arable farm land
• transition
• crop choice
• biomass demand
• food demand
decision-making process
data
farmers
simplification & classification
wind energy
• construction (cost)
• electricity price (benefit)
conditions
bioenergy
• yield
• crop price
equations, optimization procedure
consequences
energy coordination
• bioenergy
• wind energy
land use strategy
• agricultural land
• land for wind turbines
crop choice
• wheat
• rapeseed
• sugar beet
• potatoes
• silage maize
• switchgrass
• miscanthus
wind farm allocation
• wind farm location
• number of individual turbines
scenarios
feedback
dynamics of land use patterns


grain markets
crop production
biomass-based power plant (i)
bioenergy
farmers (r)
energy grid
wind farms (j)
wind energy



area of food crops [kha]
500
450
400
350
300
250
200
150
100
50
2010
2020
2030
2040
2050
area of energy crops [kha]
200
180
160
140
120
100
80
60
40
20
0
number of bioenergy plants
700
600
500
150
100
50
0
number of wind turbines
3000
2000
1000
0
North Sea coast reference scenario
North Sea coast medium subsidy
North Sea coast high subsidy
landlocked Schleswig-Holstein reference scenario
landlocked Schleswig-Holstein medium subsidy
landlocked Schleswig-Holstein high subsidy
Baltic Sea coast reference scenario
Baltic Sea coast medium subsidy
Baltic Sea coast high subsidy

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