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BIOMASS & BIOENERGY

‘Energy landscapes’: Meeting energy demands and human aspirations

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A B S T R A C T

Renewable energy will play a crucial role in the future society of the 21st century. The various renewable energy sources need to be balanced and their use carefully planned since they are characterized by high temporal and spatial variability that will pose challenges to maintaining a well balanced supply and to the stability of the grid. This article examines the ways that future ‘energy landscapes’ can be modelled in time and space. Biomass needs a great deal of space per unit of energy produced but it is an energy carrier that may be strategically useful in circumstances where other renewable energy carriers are likely to deliver less. A critical question considered in this article is whether a massive expansion in the use of biomass will allow us to construct future scenarios while repositioning the ‘energy landscape’ as an object of study. A second important issue is the utilization of heat from biomass energy plants. Biomass energy also has a larger spatial footprint than other carriers such as, for example, solar energy. This article seeks to provide a bridge between energy modelling and spatial planning while integrating research and techniques in energy modelling with Geographic Information Science. This encompasses GIS, remote sensing, spatial disaggregation techniques and geovisualization. Several case studies in Austria and Germany demonstrate a top-down methodology and some results while stepwise calculating potentials from theoretical to technically feasible potentials and setting the scene for the definition of economic potentials based on scenarios and assumptions.

1. Problem statement

1.1. *The demand for renewable energy sources*

Most societies are experiencing a dependence on fossil fuels that is increasingly problematic. The need to make increasing use of renewable energy sources is discussed in published scientific literature [1] and reflected by policies in many parts of the world, most notably the European Union and Japan. Electricity generation currently supplies about 18,000 TW-hours of energy per year, which is around 40% of humanity’s total energy use. In doing so it produces more than 10 Gt of carbon dioxide every year, the largest sectoral contribution to humanity’s fossil fuel derived emissions [1]. There is a wide range of technologies using, for example, solar, wind, nuclear, and geothermal energy, that can generate electricity with no net carbon emissions. The potential benefits of using renewable energy are repeatedly emphasised in the literature and include a decrease in external energy dependence, a boost to local and regional

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component manufacturing industries, the promotion of regional engineering and consultancy services specializing in the utilization of renewable energy, an increase in R & D, a decrease in the environmental impact of electricity production and transformation, an increase in the level of services available to rural populations, and the creation of employment, etc. [2–4].

While the desirability of renewable energy is not in doubt, comprehensive assessments of its sustainability that include energy production, transportation, and consumption are, at present, not generally carried out. Several consequences resulting from the use of these substitutes for fossil fuels, and from their transportation, may place considerable pressures on the environment, and there is also some concern regarding the sustainability of present and future patterns of energy consumption. For instance, when evaluating the performance of solar energy systems using exergy analysis, calculation of the exergy of radiation is crucial but can be problematic, since exergy represents the maximum quantity of work that can be produced in a given environment, and the terrestrial environment is considered to be an infinite heat source or sink [4,5]. Renewable energy sources are characterized by their temporal and spatial variability, which is in contrast to fossil fuels. At least one local source of renewable energy can typically be found at almost any location on the Earth's surface. Only recently electrical engineering and planning have begun embracing 'second-law thinking' to reduce energy consumption in the built environment [6].

The broad spectrum of renewable energy resources available compared to conventional resources also complicates the energy system and challenges the stability of an energy grid. Although there is a growing body of literature dealing with the transition of socio-technical systems towards sustainability and the system innovations that this requires (e.g. [7,8]), most of these publications do not include a single map.

1.2. *Bioenergy*

Timber, crop residues, and other biological energy sources are important for more than two billion people [1]. These fuels are mostly burned in fires and cooking stoves, but in recent years biomass has also become a source of fossil-fuel-free electricity. Bioenergy promises to bring a shift in the geopolitics of energy. Many regions with a high production potential want to become oil and gas independent, and green fuel exporters [1]. The assessment of projected global biomass and bioenergy production potentials for 2050, originally published by the IEA Bioenergy Task 40 and summarised by Junginger et al. [9], highlighted some regional potentials and identified sub-Saharan Africa as holding the greatest bioenergy production potential, followed closely by Latin America and Russia. The EU and the US ranked somewhere in the middle and could become biofuel importers. In Asia the situation was more complex: eastern Asia, together with China, was seen to hold considerable potential, but not Japan. Southeast Asia, together with India, would not be able to produce enough bioenergy given their rapidly increasing populations. Australia and the Pacific Islands could become big exporters, since they would be able to produce nearly six times more bioenergy than their future requirements. Low production figures were estimated for the Middle East, with its sandy deserts. The report concluded by saying that Africa and Latin America will find that the global shift towards biofuels and bioenergy offers an opportunity to produce for a global market and to derive power from this trade, while bioenergy-deprived countries such as Japan will have to choose between competing for increasingly scarce hydrocarbon reserves, or making energy deals with green superpowers.

In 2009 the European Union (EU) introduced the Renewable Energy Directive [10] with the overall objectives of increasing the security of energy supplies and reducing greenhouse gas emissions, and with practical goals of 20% renewable energy by 2020 accompanied by sustainability schemes (*EU Sustainable Development Strategy*). The targets not only include a 12% renewable energy share of the total electricity consumption, but also a 5.75% bio-fuel share of the total fuel consumption. These targets can be fulfilled by a supply of about 300 million wet tonnes of biomass. At the same time the EU agreed to try and halt the loss of biodiversity within its member states. One measure adopted involved the creation of the Natura2000 network of important nature sites, covering about 20% of the EU land surface. However, additional nature conservation and restoration sites will need to be designated if the biodiversity target is to be met. There are concerns that an increased cultivation of bioenergy crops will decrease the land available for nature reserves and for traditional agriculture or forestry. Various projects have been initiated at an operational level; for instance, to assess possible negative impacts of bioenergy on ecosystems, the European Forest and Agricultural Sector Optimization Model (EUFASOM) simultaneously assesses economic and environmental aspects of land use. Other authors analyse the potential effects of bioenergy production on European wetlands by integrating a spatial wetland distribution model with EUFASOM [10] while considering the costs and benefits of measures as well as their consequences for agriculture and forestry. According to [11] bioenergy targets have measurable effects on conservation planning and nature conservation. These authors exhibit that wetland targets in one place stimulate land use identification elsewhere due to market linkages. In particular, conservation and restoration of large wetland areas impact food production, consumption, and market prices.

About 6–7% of the total energy consumption within the EU currently comes from renewable energy, with biofuels accounting for 1–2% of the total fuel consumption. It is estimated that about 17.5 million hectares would be needed to meet the short term 10% biofuel target [10], which would account for roughly 10% of utilised agricultural area (UAA) within the EU. Furthermore, to reach the EU targets for 2020, 30 to 45 million hectares would be needed (45 million if only 1st generation biofuel technologies are used, according to a study by the OECD – see ref. [9]). This is clearly likely to have significant effects on land use and biodiversity, as well as on other ecosystem services. Problems include the conversion of cropland (especially that with perennial crops) to biomass crops, which may lead to increased diversity in cropping patterns and lower input uses, but on the other hand higher landscape structural diversity, which may have positive direct or indirect effects on biodiversity. For forestry, the harvesting of logging residues in a sustainable way is possible if properly managed. A controversial discussion (see, e.g. [11]) is whether or not nature reserves should contribute to biomass production under particular management controls. The use of abandoned agricultural land may restore land-use-dependent biodiversity.

Although forestry and agricultural areas provide the majority of biomass energy resources, both at present and most probably in the future, there are significant potential land resources for biomass cultivation that may have less impact on biodiversity, including:

- street plantations and roadside verges,
- urban greens,
- recreation areas,
- waste dumps and contaminated sites.

These "additional" types of areas – as compared to the mainstream debate focussing on forestry and agriculture – are supposedly less problematic in terms of their impacts on biodiversity since removal of biomass is part of their normal maintenance. Conversion of removed biomass into energy or other products increases the economic efficiency of the management of these areas, as well as including improvements to environmental quality, with indirect positive effects on biodiversity at a local level.

The explicit assumption that the EU will not be able to achieve the goals of the Renewable Energy Directive without importing energy, combined with the absence of any rules governing such imports, has set in motion a series of questionable incentives for developing countries in the field of bioenergy production. Although information remains scarce, evidence is mounting that the Renewable Energy Directive is promoting serious socially and environmentally detrimental activities outside the EU's borders ([12,13]). Countries in the southern hemisphere are increasingly perceived as potential producers in order to meet the increasing global demand for biofuels, as well as for food crops and minerals. Southern and eastern Africa in particular have become attractive areas for land investments [14].

1.3. *Ecosystem functions, ecosystem services, landscape services, and sustainable landscapes*

Ecosystems and (energy) landscapes are both complex subjects but in recent years a large body of literature has been produced on these matters and the major principles such as hierarchy theory appear to be generally agreed ([15,16]). Recent frameworks translate ecological complexity (structures and processes) into a more limited number of ecosystem functions [17] which in turn provide the goods and services valued by humans. In ecological literature the term "ecosystem function" has been subject to various, sometimes contradictory, interpretations [18]. Ecologists have sometimes used the concept to describe the internal functioning of an ecosystem (e.g. maintenance of energy fluxes, nutrient (re) cycling, food–web interactions), but a majority of scientists appear to agree with the definitions of Costanza et al. [19] and de Groot [17], which relate the term to the benefits derived by humans from the properties and processes of ecosystems (see also ref. [18]), which are all together commonly referred to as 'ecosystem services'.

Spatial planning and energy modelling have, to date, been treated as two separate domains. While energy policies are largely concerned with the security of supply, which is a challenging multi-faceted and multi-scaled issue requiring long term solutions, increasing emphasis is being placed on the need for 'local' energy production. Improvements in current energy systems with regard to CO_2 emissions and security of supply are, however, particularly dependent on spatial and temporal issues. To date, the energy industry has paid only minor attention to geospatial aspects in modelling possible future energy systems and solutions. Blaschke et al. [20] have pointed out the importance of the spatial distribution of renewable energy carriers to their possible utilization in the energy system. In addition, spatial planning in most European countries – except at the local level – does not deal explicitly with "energy spaces", e.g. with reserving space for future energy corridors and for "space-consuming" generation of renewable energies, such as biomass production. As mentioned above, renewable energy sources are characterized by their temporal and spatial variability, in contrast to the distribution of fossil fuels, and one can typically find at least one local source of renewable energy at almost any location. However, this advantage of having a broad spectrum of renewable sources compared to conventional sources complicates the energy supply system. Of the different renewable energy carriers biomass is the only one that can be reasonably easily stored and the sharp temporal variations in the availability of, e.g. wind energy and solar energy, can thus be compensated to some degree.

Another concept that needs to be discussed briefly is that of sustainability and 'sustainable landscapes' [21,22]. According to Antrop [21] the idea of landscape sustainability can be interpreted in two ways. Firstly, the idea can refer to the conservation of certain landscape types or values and implicitly, the continuation of practices that maintain and organize these landscapes. The idea of sustainability is not restricted to particular types of landscapes, which can be natural or cultural, traditional or contemporary, spectacular or ordinary, or – in the context of this paper – 'energy landscapes'. The concept can be applied to practices that maintain traditional techniques in rural or pastoral landscapes, but it can also refer to the land qualities of natural landscape remnants, or of new, contemporary landscapes. Secondly, the idea can refer to sustainability as a major principle for future landscaping. In this case, the concept refers to potential landscapes which will need to improve their sustainability, in particular in rural countryside planning and management.

2. Methodology

2.1. *Research challenges*

Renewable energy sources are manifold and vary greatly in their spatial and temporal availability. As well as the usual classification of energy carriers according to the media involved (wind, water, biomass ...), supply options can be broadly divided on the basis of the underlying energy transformation process [23]:

- Mechanical supplies, such as hydro, wind, wave and tidal power. The mechanical source of power is usually transformed into electricity at high efficiency rates, e.g. 35% for wind or 70–90% for hydropower.
- Heat supplies, such as biomass combustion and solar collectors, provide heat with efficiency rates of 20–35%.
- Photosynthesis, photochemistry, and direct photovoltaic conversion may only reach conversion efficiencies of 15–30%.

The problem faced in this context is the generally low energy density of renewable energy carriers, which requires a greater emphasis on geographical variations in renewable energy supply and energy demand. Although utility providers make extensive use of GISs they have so far been mainly thinking "along lines", i.e. concentrating on the existing grid structure rather than on potential supply and demand areas. However, in order to reduce the increasingly problematic dependency on fossil fuels, national and regional policies will need to take greater responsibility for securing energy supplies. Master plans and policy decisions must be based on hard facts, many of which can and should be based on geographic footprints and make use of geospatial techniques.

The amount of final energy required is determined by the amount of energy services available and the qualities of the corresponding application technologies, and the demand is affected by the thermal structure of buildings, the efficiency of machinery and appliances, etc. [24]. We therefore conclude that spatio-temporal modelling of energy resources and demand should not involve just a simple juxtaposition of energy supply/potential and energy demand, but should also consider the spatial and temporal characteristics of each energy carrier and the characteristics of each individual subset of a region at an appropriate scale. Fig. 1 illustrates that there is usually not one single appropriate scale for any given subset of the world – including landscapes and 'energy landscapes' – rather, we need to accommodate application- and context-specific instantiations of the latter.

Schleicher ([24], modified here) identifies three key qualities that will be required in future energy systems:

- low energy usage, as a result of switching to high-efficiency application and transformation technologies,
- low carbon emissions, achieved by the phasing out fossil fuels and increased use of renewable energy, and
- low transport distances, achieved by realising the potential of locally available energy sources including solar, wind, hydro and biomass applications.

For a more 'complete' picture it would be necessary to discuss the need for novel engineering, regulatory, and financial solutions (including pricing), but this goes beyond the scope of this paper. It should just be mentioned that most current regulatory solutions do not require information from the customers concerning their priorities, e.g. willingness to pay for short-term improvements to the quality of service, long-term supply guarantees, or reduced greenhouse gas emissions.

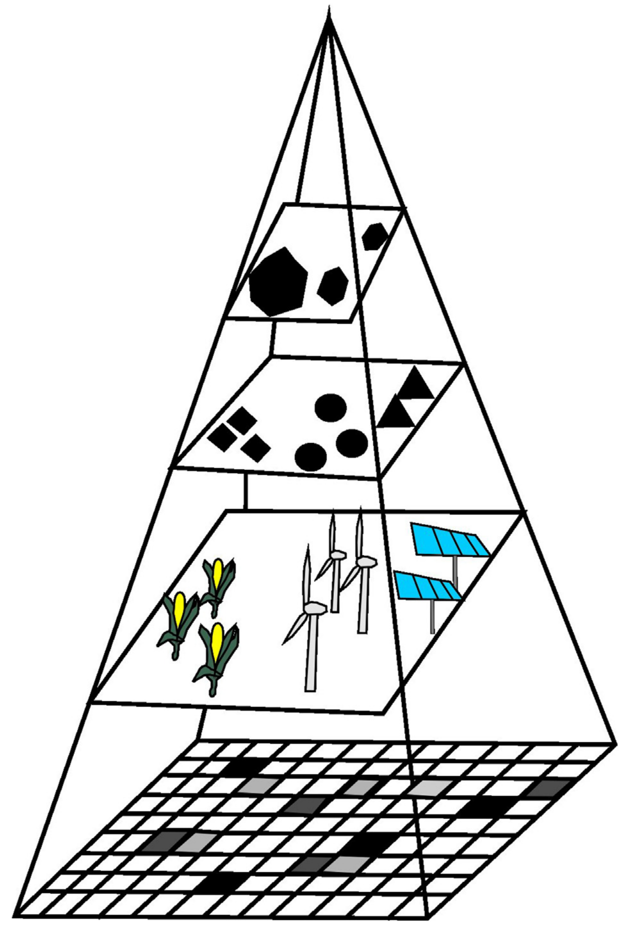

Fig. 1 – Defining the appropriate scale is one of the challenges faced by landscape research.

2.2. *GIS and spatial data infrastructures*

Geographic Information Systems (GISs) are today considered to be a mature technology. The consumer community, as well as decision and policy makers, have realized the importance of making sound decisions based on information derived from properly designed geospatial databases. Organizations have created their own proprietary geospatial databases, governments are rethinking the contents of their national spatial data infrastructures (SDIs), and worldwide attempts are being made to develop a Global Spatial Data Infrastructure (GSDI) and a Global Earth Observation System of Systems (GEOSS). Extensive geographic data acquisition programs including satellite imagery, digital aerial photographs, and Light Detection and Ranging (LiDAR) systems at varying ground resolutions, as well as land parcel data, are currently in progress around the world. Technologies such as the Global Positioning System (GPS) and digital image processing software have also facilitated the data processing aspects of these projects. The consuming public has become increasingly aware of the benefits of geospatial information. Web-based applications are leading to data accessing and processing techniques such as "mash-ups" and cloud computing services, through hosted content and virtual machines that process data from disparate locations.

For many years GISs as well as other data management and decision support systems were developed separately for a variety of purposes, but there was no uniform, integrated and coherent information systems framework directed towards proactive planning and policy-making. They have, however, now ended their stand-alone history and grown into mainstream IT frameworks, applications, and workflows. Efficient techniques for representing a wide variety of data have been developed in recent years. One reason for historical deficiencies in these systems was that the conceptual models employed for digital geographic data representation did not take into account how humans store and use geographic information [25]. These shortcomings in the ability of conventional GIS data models to present information in a way that is more 'natural' to humans are today widely acknowledged. There is a well established tradition in geographical research of exploring how humans represent environments dependent on 'their' scale ([26,27]). Mennis et al. [28] believe it is this perspective, combined with the variety of cognitive evidence from psychology that needs to be integrated into GIS database design in order to improve geographic database representation. We want to demonstrate in this article that a GIS database should not simply present a logical view of spatial data, but should also represent a derived higher-level of knowledge that corresponds to the community's (the user's) appreciation of a topic, which in this case is energy demand and renewable energy production potentials. While a number of GIS researchers have explored the characteristics of cognitive representation and conceptual modelling (e.g. ref. [29]), it has taken many years for their findings to be incorporated into a usable framework for database representation. Raper and Livingstone [30] were perhaps the first to come close, having developed a specific representation for observational geomorphologic data within a cognitive context.

With the maturation of GIS technology and especially with the advent of virtual globes such as Google Earth or Google Maps, a mass market has developed with a demand for spatially explicit information. Beyond proprietary geospatial databases, spatial data infrastructures (SDIs) such as the USA's NSDI have been developed to facilitate interoperability between data sets and meta-data standards, and to broaden access to information. Extensive geographic data acquisition programs – briefly mentioned above – are capturing the world in increasing detail. Broad user access to Internet-based geospatial information has made the consuming public more aware of the potential benefits of geospatial information and of related services available through the Internet. Remote sensing has technically matured quite significantly over the last 10–15 years. Ongoing challenges discussed in remote sensing literature are those of scale ([31,32]) and, to a lesser extent, the modifiable areal unit problem (MAUP). In this paper we describe a framework for geographic representation that uses GIS as the baseline technology, with the objective of allowing explicit consideration of the spatial and temporal domains within the energy context by making the underlying assumptions and rules explicit. Biberacher [33] and Biberacher et al. [34] developed a generic framework within which to integrate different analysis methods for energy demand and renewable energy potentials. The proposed framework and the modelling approaches based upon it allow geographical models to be derived that are capable of representing both observational data and higher-level abstractions that can be derived from that data combined with external expert knowledge.

2.3. *GIS-based biomass modelling*

Energy modelling is often limited by being reduced to energy modelling within grids. General systems theory [35] provides a conceptual framework within which systemic entities can be organized. The spatial manifestation of this organisational structure produces certain particular patterns. Understanding the relationships through which these patterns are formed is a key to understanding the systemic properties. Patterns themselves can only be understood by mapping them and then investigating their configurations [36]. Patterns are specific and in their specification they are viable for organisms. An additional aspect of systemic organization that should be briefly mentioned is that systemic entities show emergent properties through self-organization, including feedback control and mechanisms of self-regulation. This concept has been applied to the development of 'autarchic energy regions' [37]. Biberacher [37] and Biberacher et al. [34,38] presented a top-down modelling approach to estimate the potentials for several different renewable energy sources. These theoretical potentials are based on topography, climate, land use, and many other factors. The estimated theoretical potentials are reduced to technical potentials by taking into account the technical limitations of state-of-the-art technology, factors such as slope steepness that will affect the distribution of particular renewable energy sources. Certain land use classes or protected areas will also typically be excluded. By using rather soft factors that can be modified over time and that may vary regionally, the potential can be further reduced to a realisable figure and the development and deployment of the individual energy sources can be integrated within this step guided by expert-defined assumptions. Through the use of GIS areal data, for example, values for whole municipalities and spatially explicit data in the form of vectors or rasters can be integrated (Fig. 2).

Remote sensing methods are widely used to estimate biomass. The combination of remote sensing derived information, in situ information, and a variety of GIS data stored in spatial data infrastructures, allows the spatio-temporal modelling of both supply and demand and, most challengingly, the inclusion of transportation factors and even 'complete' life cycle assessments of energy products. Section 3 summarizes results from various projects carried out for Austria. The general approach used has been described by Biberacher [33,37], Biberacher & Gadocha [39] and Biberacher et al. [34]. Blaschke et al. [19] utilized this framework in regard to climate change issues and Blaschke et al. [40] have already demonstrated that this geographically explicit modelling framework can be deployed for a variety of strategic spatial planning needs. This approach is now employed in detail for biomass modelling: for the illustration, assessment, and

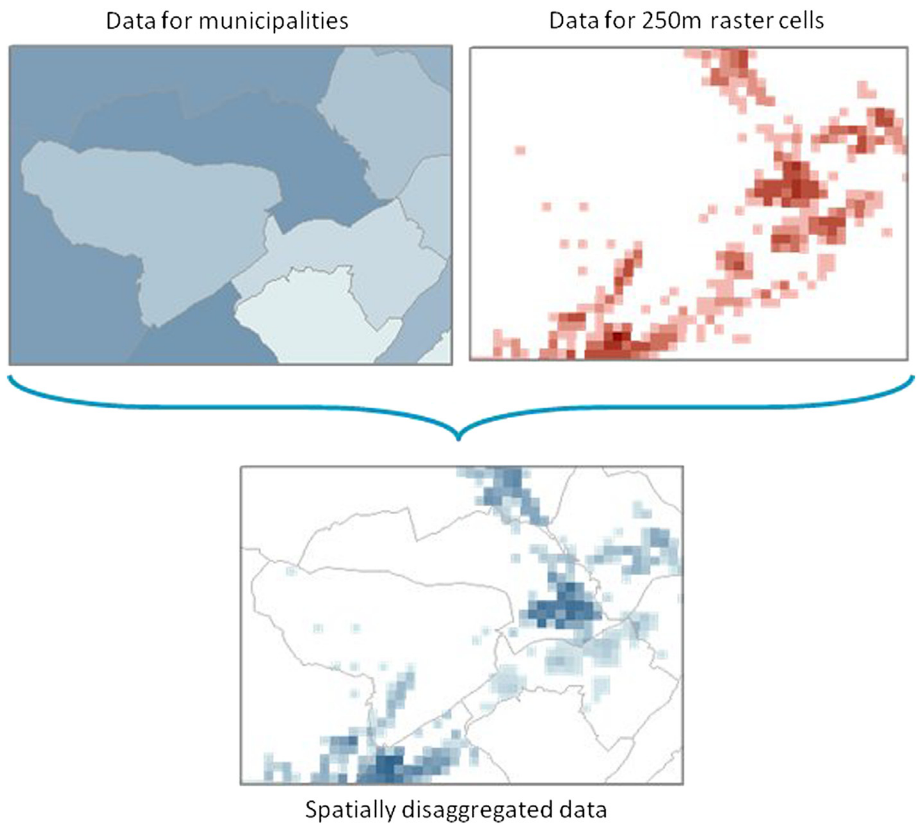

Fig. 2 – Areal population data (for municipalities) and high resolution raster data (population in Austria based on 250 m raster cells) are integrated by means of GIS, to produce spatially disaggregated data.

optimisation of biomass utilisation paths, ranging from the availability of biomass cultivation areas to their utilisation for either food or energy. The framework takes into account climatologic, economic, social, and ecologic factors and allows the generation of future development scenarios, with a special focus on climate change.

In addition to energy potentials, energy demand is assigned to specific locations and energy consumption is modelled at the same geographical resolution as the energy potentials. In order to estimate the heat and electricity demand, typical values for energy demand are either used directly or broken down into appropriate spatial units through disaggregation. Some other statistical data for households within the area of interest are also used in the estimation of energy demand. By combining these data the spatial distribution of the energy demand can be mapped. Biberacher [33] optimized the model and further enhanced the framework to incorporate spatio-temporal characteristics in energy supply and demand. With these characteristics in mind a hypothetical energy system setup can be explored using this framework.

Biberacher and Gadocha [39] presented a modelling approach to optimize ways of satisfying the demand for heating within a defined region of interest, giving precedence to renewable energy carriers and focussing in particular on spatial differentiation. Their modelling approach handles information on geographically disaggregated data on renewable energy potentials (biomass, solar energy, geothermal energy, ambient heat) on the one hand, and geographically disaggregated information on heating demand on the other. This spatial balance forms the basis for modelling optimal utilization of the space available for identified renewable energy resources in order to satisfy the heating demand with respect to the mathematical 'objective function' of the model, which is defined as obtaining the highest economic efficiency for the region within prescribed constraints for greenhouse gas emissions. All relevant spatial data, including the energy potentials, the demand structures, and other infrastructure data, are disaggregated to a consistent spatial resolution. The region of interest is segmented into a collection of raster cells, which form the smallest spatial unit in the model. The size of the raster cells is 250 m × 250 m. In recent studies the modelling approach has been extended to a more holistic analysis of a region and to spatial scenario techniques (e.g. [41]). Angelis-Dimakis et al. [42] recently presented an overview of methods and tools available to determine the potential and exploitable energy from some important renewable energy sectors, namely the solar, wind, wave, biomass and geothermal sectors.

2.4. *Spatio-temporal biomass modelling*

Optimising land use in conjunction with, and usually in competition with, biomass utilisation paths represents an increasing challenge in the context of climate and energy policies. The sustainable and efficient use of available land areas is therefore more necessary than ever. The modelling approach presented by Biberacher and Gadocha [39] can contribute substantially to the development and implementation of optimised, regionally specific and spatially explicit biomass utilisation strategies. In this modelling approach the geographically explicit growth rates and yields of relevant crops, crop rotations, grassland and forest types, and the demand structures for energy in terms of heat and electricity, are estimated on the basis of regionally specific conditions. The demand for food and biofuels in the region of interest is also estimated and included within the model's framework.

In the example presented in Section 3 the model implemented uses a raster-based approach. It is intended to obtain a spatial resolution of 250 m. Apart from the explicit inclusion of local conditions regarding the feasibility of utilising biomass this approach also includes the geographic setup of the existing and future biomass utilisation system. Regional statistical data and land use data on a raster basis form the main database for the model framework. The model also makes use of data on possible climatic influences and variations, as well as on cost structures and ecological and social factors. On this basis feasible utilisation strategies are identified for particular types of biomass within the region of interest, as well as their relative contributions, in an optimal setup for biomass use in the region. Emissions, costs, ecological factors, and land use competition are all relevant criteria for this integrative assessment and optimisation approach.

Individual scenarios for optimised regional biomass utilisation are illustrated, based on different assumptions for future biomass price developments as well as aspects of climate change. The modelling results encourage awareness and provide a basis for decision-making processes regarding regional biomass strategies. The model results offer vital support for regional participatory processes and illustrate causal connections within the utilisation of biomass resources. In addition, cartographic visualisations encourage awareness of possible future changes.

2.5. *Integrating the human dimension to the energy landscape concept*

The concept of an energy landscape – like the landscape concept in general – may appear vague and difficult to grasp, being viewed from different perspectives by different disciplines. It is a concept in which object and subject overlap and interact. A large body of literature elaborates that the term landscape does not simply refer to the environment, but to the world 'as perceived by people' (European Landscape Convention, Article 1a). This widely-accepted understanding allows the concept of landscape to be used to make connections between people, between people and places, and between society and its environment ([43,44]). To date, the concept has not been very much used in connection with energy planning. The authors, however, herein suggest on the basis of literature research that the concept of an energy landscape may be useful in dealing with the challenges regarding renewable energy production that face society in the 21st century.

The landscape is a powerful, diverse, and dynamic cultural resource for mankind. In many ways it is as much part of our culture as a literature, art, and language. Whereas the environment provides the inescapable physical setting for human existence, landscapes, both urban and rural, provide a concept of 'place' that is linked to the community, an ability to transform perceptions of the world across physical and psychological boundaries, a framework for people's lifestyles and identities (which in the past shaped nationhood, but now contribute to emerging sub-national and supra-national identities), and an interface (through concepts such as biodiversity) between people and nature.

When applying the landscape concept to the energy domain one challenge is that landscape research embraces a multiplicity of topics: history as well as ecology, thoughts as well as actions, and also the physical environment. By way of contrast, energy research has so far been mainly driven by technical, science and engineering concepts. The closest connections between energy research and the landscape concept were attempts for 'autarchic energy regions' or 'virtual power plants'. We suggest to putting forward the basic concept of "virtual" worlds in which people can create identities and social interactions. In these multi-disciplinary and transdisciplinary attempts research needs to be able to harness the power of landscape to assist in managing inherited landscapes, and in planning and designing "sustainable landscapes" [22]. Possibly less well known to energy modellers and engineers are methodologies such as participatory approaches, archive- and field-work, or mapping, as part of a long tradition of studying landscape as personal and collective cultural constructions, although ten years ago [45] investigated already the conflict between society's landscape appreciation and technology when studying a wind energy landscape in California.

A purely technical view on energy demand and supply may be regarded as a reductionistic view. The landscape as a concept expresses the ways in which places matter to people culturally and materially in everyday experience, and how it symbolizes the power and complexity of social formation and cultural identity. According to Antrop [21] the rural landscape may be regarded as a space with many different functions. The meaning of landscape shifts then more towards the concept of *location* than its more original significance as *place* (*ibid*.). Since "The countryside is becoming a place for living, not for making a living" [46], the relationship between residents and their environment is changing completely. Following these lines of arguments and by applying Austad's [47] six strategies to "energy landscapes" we can expect that (bio)energy landscapes will involve:

- The concepts behind traditional (according to [47]:'authentic') cultural landscapes: bioenergy production should preferably be based on semi-natural vegetation types and traditional agricultural systems that are valuable because they have proved to be sustainable over centuries and serve as good models for bioenergy production and, ultimately, for "energy landscapes".

- Stimulating the revitalization of inferior land areas ("outfields" according to [47] and intensification of low-intensity farming systems.
- Incentives and financial support for farming regimes that maintain biological and/or historical values.
- Encouragement of the principles of organic farming and agroforestry.
- Combining local knowledge and traditions with concepts of landscape ecology and energy/exergy concepts, to develop 'new' cultural landscapes and agro-systems.
- Research into traditional sustainable agriculture with respect to energy use, in particular biomass consumption, and application of the results of this research.

2.6. *"Energy landscapes": more than "energy regions"*

The concept of regions is well established and is, for instance, a core concept in geography. Abler et al. [48] outlined the principal ideas. Without repeating them here we need to state that political sciences have developed their own notions and their own terminologies. Their concept of regions has been attracting a lot of scholarly attention lately. The European Union is one example where regions play an important role as political surrogates for regional identities, while others may regard them simply as leftovers of provincial mentalities not yet absorbed into an idealized nation state. Today regions are often seen as places of resistance to centralized authority and "harbingers of reform and democracy" (e.g. the case of Istria in Croatia [49]). Regionalisation concepts do not, however, necessarily coincide with landscape concepts. Geographers, cultural sociologists, landscape ecologists and many other scientists have been, and still are, particularly interested in the impact of different cultures on the Earth's physical surface and, conversely, in how physical settings have influenced the emergence of cultures. The composite of human imprints on the Earth's surface is called the cultural landscape, a term which is widely used today having originated from the work of German geographers and been promoted by the American geographer Carl Sauer during the 1920s. Sauer [50] proposed a straightforward definition of a cultural landscape in which forms are superimposed on the physical landscapes by the activities of man. While referring to Blaschke [22] Potschin and Haines-Young [51] argued that if landscape ecology is to make a significant and distinctive contribution to contemporary debates about sustainability, then it is likely to be based on one of the discipline's core assumptions, which is that spatial patterns matter. Blaschke [22] discussed the pros and cons of the natural capital paradigm [52] and the analysis of landscape structure based on the ideas of Forman [43].

The concept of "energy regions" is appearing with increasing frequency in scientific literature although it is predominantly used metaphorically, or at least, very few publications include maps of real landscapes. The term "Energy landscape" was discussed by [53]. Späth and

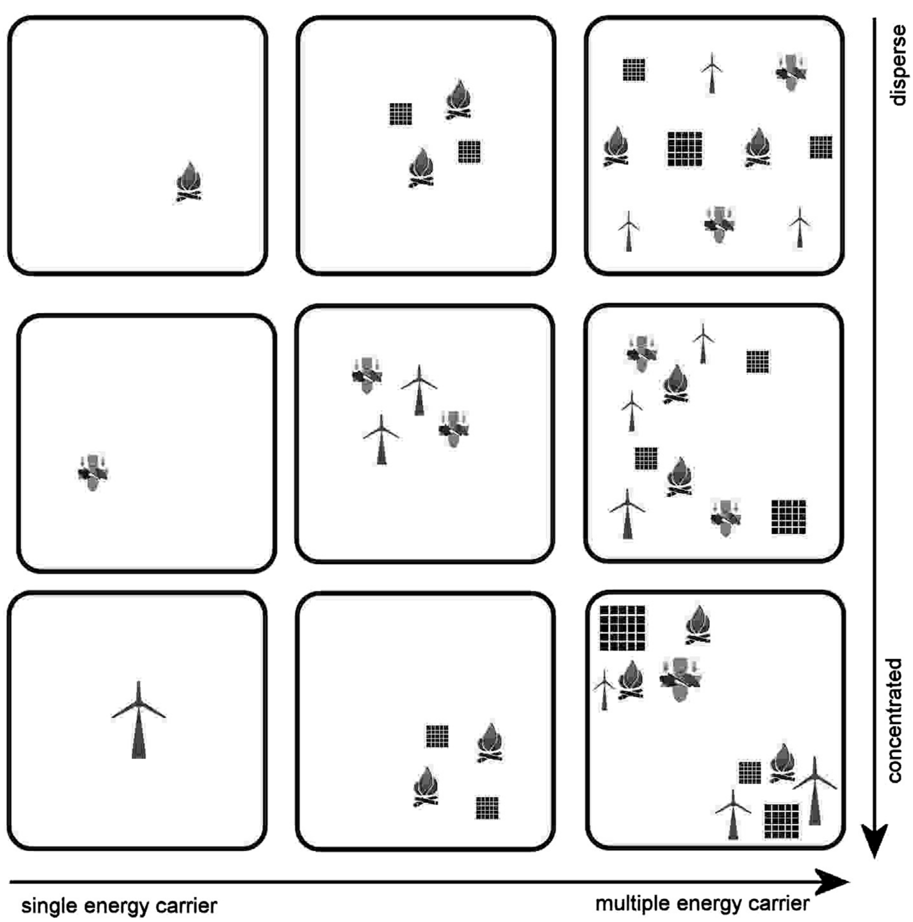

Fig. 3 – Envisioning spatial patterns in the production of renewable energy: SLOSS; single large or several small?

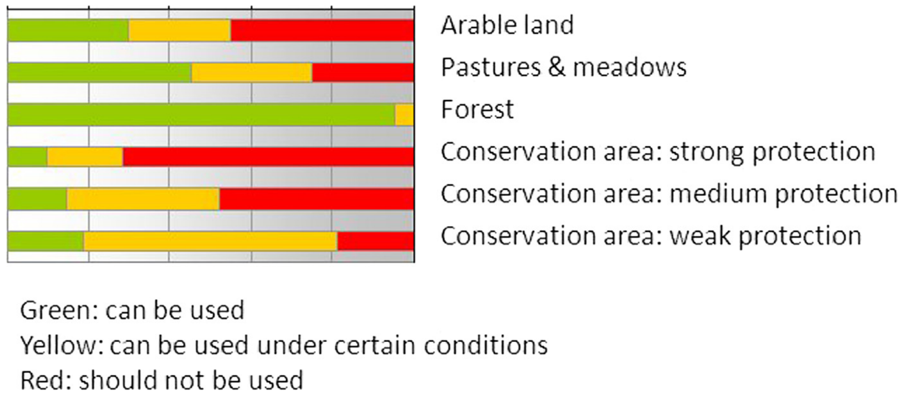

Fig. 4 – Expert opinions on the use of six different land use categories for forest biomass (as distinct from agricultural biomass, not displayed here). Translated from ref. [59].

Rohracher [8] theoretically utilized this approach to "energy regions" in Austria. This can be seen as an interesting example of the strategic promotion of guiding visions in the context of regional development. As a case study they describe an alpine district in Austria in which a strong actor network has been built around a vision of systematically exploiting renewable energy sources, at the same time saving the region from economic decay. One of the few convincing examples of an "energy landscape" is described by Moser et al. [54] who were aiming to achieve a 100 percent renewable energy region in Germany. According to these authors people are most directly affected by any activities at a regional or local level, whereby (energy) regions are understood to be complex geographic territories that are sized in such a way that they can serve as relatively homogeneous areas with regard to renewable energy supply. They argue that visible changes, that are both socially and spatially integrated, support the concept of a strong regional identity.

Due to limited space we can only briefly refer here to the differences between the notions of 'region' and 'landscape'. The concept of landscape encompasses more than an area of land with a certain use or function. Referring to Zonneveld [55] we consider landscape as a synthetic and integrating concept that refers both to a material-physical reality, originating from a continuous dynamic interaction between natural processes and human activity, and to the immaterial existential values and symbols of which the landscape is the signifier. Alexander von Humboldt defined landscape concisely as "der Totalcharakter einer Erdgegend" [55]. The ultimate question in this context is, therefore, whether 'regions' or 'landscapes' provide adequate scope for strategic concepts and creations within legal spatial planning frameworks. In this context, Moser et al. [54] argue that the application of a range of technologies for renewable energy use involves different players as well as different spatial perspectives, the smallest spatial entities being a building, then a quarter, village or district. They correctly state that supply systems can usually only be analysed with respect to their autarchy at a regional level. Understandably, regions are the notion of choice for the planning of wind parks or smart grids and they are the focus of

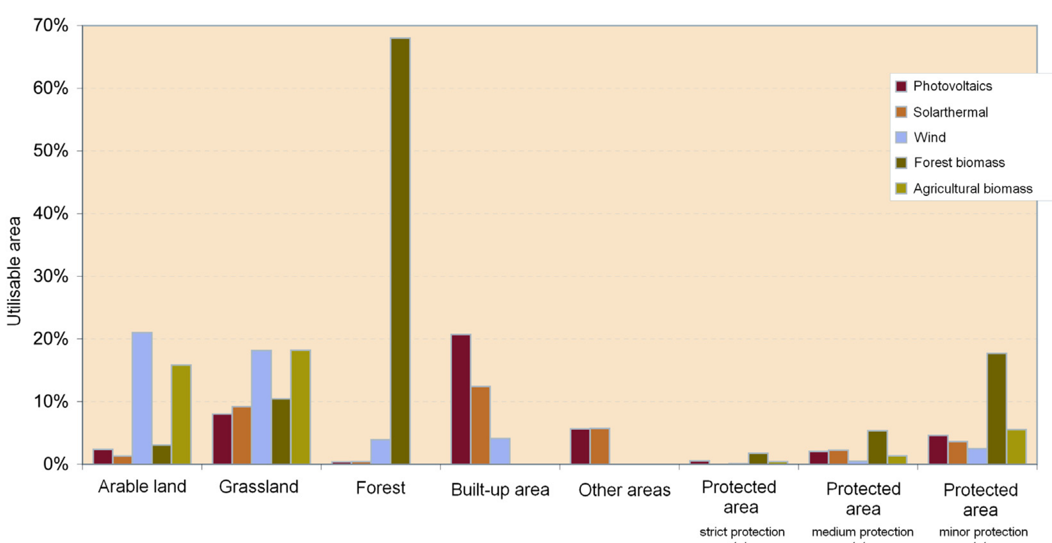

Fig. 5 – Different land use categories and their respective shares which are potentially technically usable – based on expert opinions. Translated from ref. [59].

Table 1 – Thresholds for several renewable energy barriers based on estimates by 21 Austrian experts.

	Average distances of expert opinions [m]				
	Photo-voltaics	Solar-thermal	Wind	Biomass forest	Biomass agricult.
Maximum distance to transportation network	–	–	233	400	500
Maximum distance to heat consumer (e.g. settlements)	–	171	–	5500	10,000
Minimum distance to settlements	–	–	900	–	–
Minimum distance to transportation network	–	–	244	–	–
Minimum distance to airports	–	–	1250	–	–
Minimum distance to protected areas	–	–	994	–	–
Average yearly minimum wind speed [m/s]	–	–	5	–	–

many planning programmes. 'Regions' may be less adequate when incorporating human dimensions including feelings and values attached to particular places. They may also cater less for historic values and cultural achievements. In summary we may claim that (a) 'regions' express and bear predominantly an economical view and (b) that they are less able to cater for pattern, which is an aspect of spatial organisation that is important when considering temporal aspects.

An analogy can be made with the "SLOSS" debate, which originated in nature conservation: it was debated for more than a decade whether, if resources for nature conversation are limited, it would be better to have a single large reserve or several small reserves. This was a product of the island-biogeographic foundation for reserve design theory, and ended in the inconclusive answer, "it depends" [56]. Possingham et al. [56] make the case that close and well connected patches may be a disadvantage if the arrangement increases correlations among reserves in environmental variation, by inviting disease, exotic species and/or disturbance events to pass from one patch to another. The disadvantages of such processes may outweigh any advantage to be gained from elevated dispersal rates and increased recolonisation probabilities, at least for some species [56]. This excurse to nature conservation shall guide us in the debate of energy landscapes. To the knowledge of the authors it has not been discussed in the case of bioenergy production whether or not compact arrangements or scattered arrangements are to be preferred. Fig. 3 illustrates the planning question which is rarely formulated explicitly and even more rarely answered on the basis of scientific studies and hard facts, namely, should we concentrate (renewable) energy production sites geographically by clumping them together, or should we aim for decentralised solutions? There will probably never be an unequivocal answer to such a question. However, the pros and cons of clumping them together, the associated increase or decrease in transportation needs, and the ecological and aesthetic impacts, all need to be addressed in the spatial planning of "energy landscapes".

3. Case studies and results

As mentioned previously, timber, crop residues, and other biological products are important energy sources for more than two billion people and these fuels are mostly burned in fires and cooking stoves, but over recent years biomass has also become a source of fossil-fuel-free electricity. In 2005 the

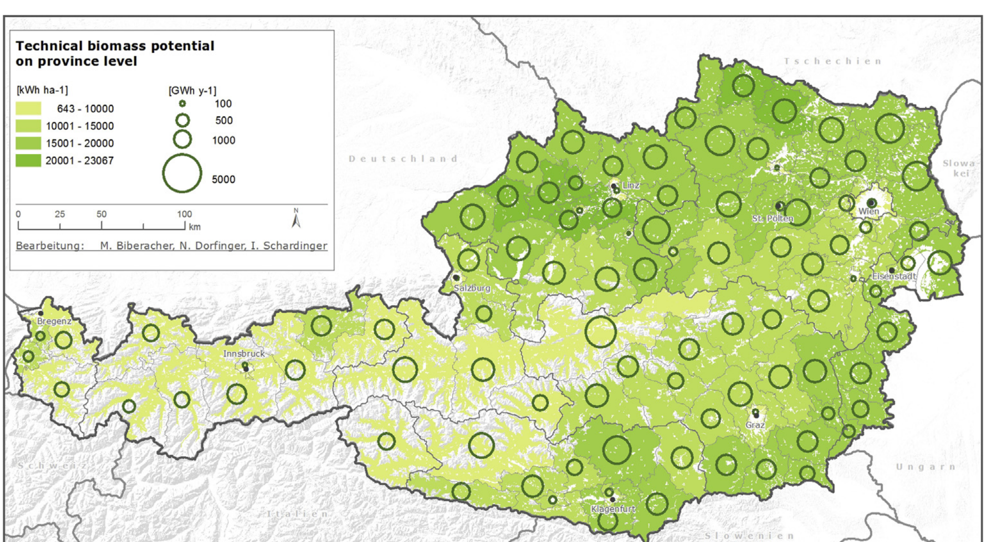

Fig. 6 – Technical biomass energy potential for Austria aggregated to 250 m cells (raster in background) and for districts (with circles at their geographic centres, and circle sizes representing the absolute biomass potential). Translated from ref. [59].

World Energy Council estimated the world's generating capacity from biomass to be at least 40 GW per year, larger than that from any other renewable resource except for wind and hydropower [1]. An important problem with using biomass as a fuel is the large spatial footprint and, accordingly, the low energy density compared to that of traditional fossil fuels. Biomass, in general, includes the above-ground and below-ground living mass, such as trees, shrubs, vines, roots, and the dead mass of fine and coarse litter associated with the soil. Due to the difficulty in collecting field data of below-ground biomass, most previous research on biomass estimation focused on above-ground biomass (AGB). In recent years remote sensing has become the main technique used for estimating AGB (for an overview see Lu [57]).

Biomass represents the potential carbon emissions that could be released into the atmosphere due to deforestation,

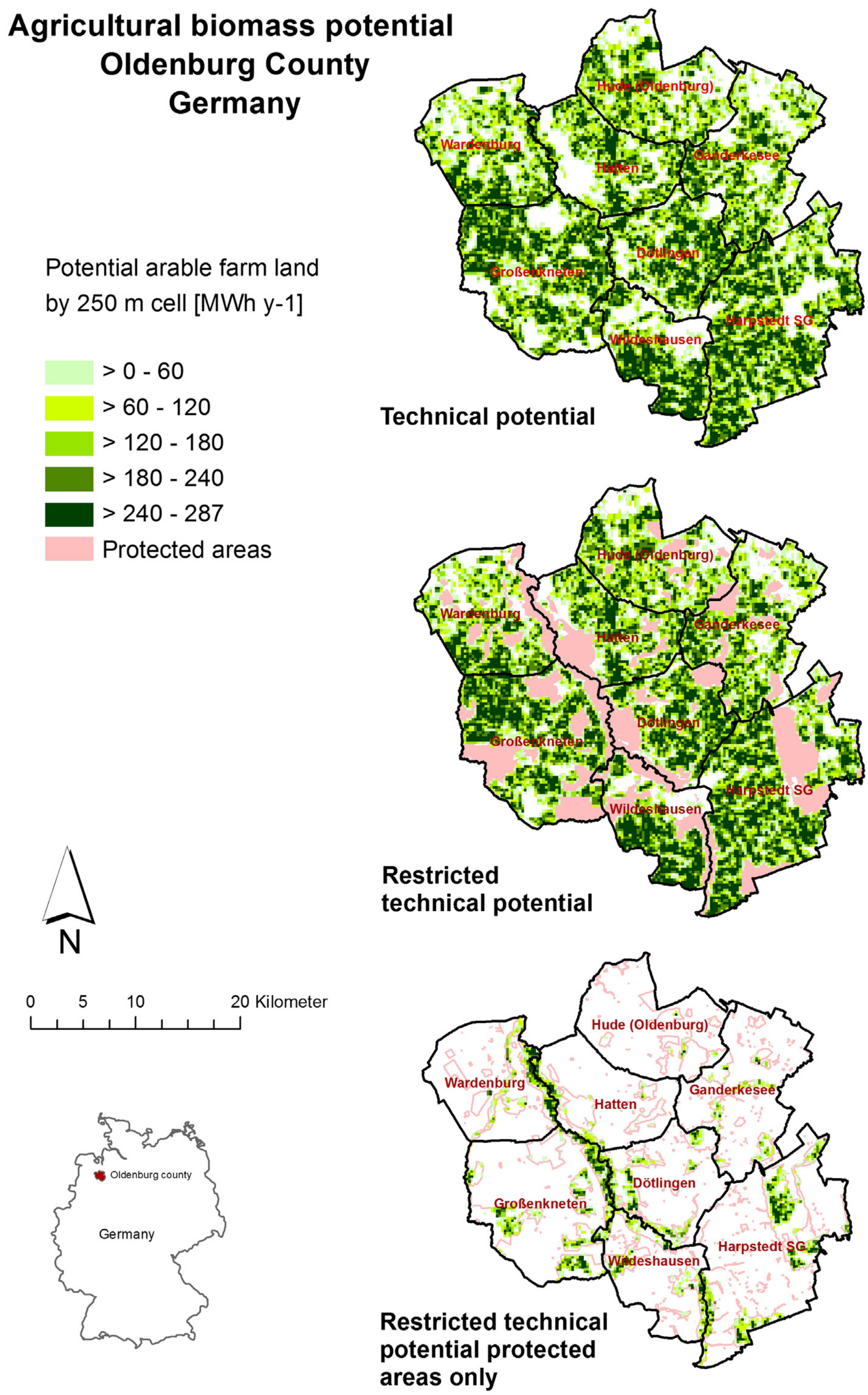

Fig. 7 – Agricultural biomass energy potential for Oldenburg county (Northern Germany) aggregated to 250 m cells: Depending on political decisions biomass from protected areas (bottom) may be excluded (centre) or included (top).

and regional biomass changes have been associated with important outcomes in functional characteristics of ecosystems, as well as with climate change. The roles of biomass and its impacts on carbon cycles, soil nutrient concentrations, fuel accumulations, and habitat environments in terrestrial ecosystems have long been recognized [57]. Accurate delineation of biomass distributions, at scales that range from local and regional up to global, becomes significant in reducing the uncertainty of carbon emission and sequestration, understanding their roles in influencing soil fertility and land degradation or restoration, and understanding the roles in environmental processes and sustainability [58]. Biomass supply is very seasonal, thus creating a need for temporarily stockpiling before and after delivery to the power, heat or processing plant. Biomass can be stored relatively well compared to other renewable energy carriers, but with high storage and transport costs.

The renewable energy carriers currently being used in Austria (biomass, geothermal, photovoltaic and wind) were assessed in a national project financed by the Austrian Conference on Spatial Planning (ÖROK [59]). Within this project an Austria-wide integrative approach was developed that allows cartographic visualisation of the spatially differentiated potentials for the various renewable energy carriers in a systematic and comparable way. It was assumed that the implementation of defined objectives would result in spatial consequences over broad areas. Scenarios were therefore developed in workshops in collaboration with national experts that would allow for a regional prioritization of energy carriers within planning programs. The potential for each appropriate individual renewable energy carrier was modelled systematically and spatially differentiated. These included solar, water, wind, biomass, ambient heat, hydrothermal geothermal energy and near surface geothermal energy carriers. A top-down approach was used for the modelling, as developed by Biberacher [33,37], and by Biberacher & Gadocha [39]. In essence, this approach starts with the calculation of the theoretical potential for each energy carrier, followed by the calculation of their technically available potentials and finally, by modelling their restricted technical potentials in various different scenarios. Assumptions such as “no wind park above 2000 m a.s.l.”, “no forest biomass potential above 1800 m a.s.l. or for slopes greater than 50°” are utilised in the GIS. Further political-social and economic restrictions such as acceptability and cost are also considered. The resulting potentials were aggregated to a provincial or district (county) level (Fig. 5). Fig. 4 illustrates how decisive the expert rules are. In fact, the technical definitions of the calculations of the potentials and the GIS have less influence on the results.

Expert opinions vary widely and can even contradict each other. Several strategies were, however, developed in this nationwide study on the basis of a consensus-finding process. Within these strategies, favourable spatial planning instruments were assigned for implementation. Those energy carriers that could be most effectively influenced by the appropriate strategy were given precedence. Two strategies developed as examples within this project were (a) legal regulation options for climate protection, and (b) coordinating existing spatial planning regulations. All strategies were based on expert valuations and their realisations in GIS. Table 1 provides average distances from 21 experts who were asked to supply minimum distances for different energy uses to six different land use categories including, for instance, settlements.

The same methodology was applied to other regions. For the district of Oldenburg in Northern Germany, 1063 km^2 in size, the renewable energy biomass potential and other energy potentials were determined. 69.000 ha agricultural land (about 70% arable land, 30% grassland) and 20.000 ha forests (48% coniferous forest, 24% deciduous forest, the rest being mixed and grove woody plants). Both potentials were calculated independently following the method of Biberacher [33,37] using regionalized input data for the energy yield. Biberacher et al. [60] calculated the average agricultural energy yield for Oldenburg County to be 5.09 kWh ha^{-1} y^{-1} and the yield for deciduous forest, coniferous forest and mixed forest to be 1.9 kWh ha^{-1} y^{-1}, 1.58 kWh ha^{-1} y^{-1} and 1.74 kWh ha^{-1} y^{-1}, respectively. Fig. 7 juxtaposes the agricultural biomass potential and the restricted biomass potential under exclusion of protected areas. The resulting biomass potential represents the total amount of biomass used for nutrition, animal feed, energy, and materials, and not to a surplus potential. In two modelling steps competing demands are reflected: for the agricultural biomass the current use for food production is deducted. Also for the forest biomass potential the recent use for timber products is modelled and deducted from the overall forest biomass potential. Based on various efficiency assumptions, the study of Biberacher et al. [60] finally reveals a gross agricultural biomass potential (without harvesting losses) of 50.9 MWh ha^{-1} y^{-1} and an average gross forest biomass potential of about 17.4 MWh ha^{-1} y^{-1} (Fig. 6).

4. Conclusions

This paper has described the notion of “energy landscapes” and some associated concepts. “Energy landscapes” 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. Such “energy landscapes” may in future become a valid intuitive concept for spatial planning and may provide spatial analysis capabilities and methods with which to plan future courses of action. We consider our framework to be a starting point, aiming to stimulate interdisciplinary discussions between physicists, energy experts, spatial planners and (speculatively), future “energy landscape” managers.

We conclude that most areas currently used for energy production, and in particular for bioenergy – which is, as repeatedly stated, a land-consuming form of renewable energy production – were not selected to meet specific predefined objectives concerning their location, quantity, and spatial arrangement. Many existing bioenergy production areas in Austria and Germany are found in places that are very suitable for other purposes (such as agriculture or urban development) or were selected for their own peculiar reasons.

What does our excursion into conservation biology and the SLOSS debate tell us about “energy landscape” design? It unfortunately offers very little in terms of guiding principles for good decision-making, but what we can learn from island biogeography theory [61] is the importance of the size, shape, and number of sites, and their spatial arrangement. GISs today may not distinguish between good and bad designs of “energy landscapes” but they do allow us to figure out optimal solutions in decision-making processes and in spatial planning, according to pre-defined criteria. The pre-defined criteria for an “energy landscape” should require a location where optimal site parameters, such as natural vegetation and human-oriented (energy) landscape services offer the best solution for the available options. Through GIS-functionality, planners are able to evaluate a range of reasonably good solutions (i.e., from an ecological perspective), in the context of other considerations, such as economics or political expediency. Today’s service oriented architectures (SOA) facilitate a much greater level of interaction between the planner and the potential solution space. Solutions can be examined and additional constraints added – such as the forced inclusion or exclusion of some sites – before running algorithms again. We may therefore conclude that the methods and tools are available – but not necessarily integrated in sound methodologies – to give planners and decision-makers the ability to evaluate a range of solutions within a general decision-making or negotiation context.

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