Optimal Renewable Energy Systems for Regions

Karl-Heinz Kettl, Nora Niemetz, Michael Eder, Michael Narodoslawsky*
Institute for Process and Particle Engineering
Graz University of Technology, Graz, Austria
e-mail: narodoslawsky@tugraz.at

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ABSTRACT

Most sources for renewable energy can be deduced from solar radiation as the main natural income of society. Contrary to conventional fossil and radioactive energy resources that are mined or pumped out from central point sources, solar energy is a de-central resource that requires area for its conversion to useful products and services. This requires a new technological as well as logistical concept for energy systems where regions play a key role as providers of energy and goods. The contribution will provide the conceptual framework for renewable energy system generation on a regional level, taking into account the responsibility of regions to provide goods and services to the larger society and to support urban centres. It will show how optimal resource-technology-demand networks may be constructed, using process network synthesis approaches and how the ecological efficiency of such regional systems can be measured. Application of these methods to real life case studies (in particular the region of Mühlviertel in Austria) will on the one hand prove the versatility of the methods presented and on the other hand will provide insight into the scope of necessary change if society moves towards a low carbon sustainable energy system.

KEYWORDS

Process Network Synthesis, RES, regions, Sustainable Process Index

INTRODUCTION

There is general agreement that fossil resources are approaching their production maximum. The time frame ranges up to 2020 for crude oil and up to 2060 for natural gas [1, 2], with coal remaining available for considerably longer time spans. These resource limitations have to be seen in combination with the discourse about global warming that requires a drastic reduction of (fossil) carbon emission. Taken together these two trends call for a dramatic change in the resource base over the 21st century, away from fossil towards renewable sources.

The change towards renewable resources however entails an equally drastic transformation of supply chains: whereas fossil resources are retrieved from typical point sources, most renewable resources are based on solar radiation either directly (photovoltaic) or indirectly (wind power, hydro power, biogenic resources based technologies) and therefore require area for their generation [3]. This puts new responsibilities into the hands of societal and political entities that exert control over land, most notably regions.

Interestingly enough, regions have become dynamic political players, most notably since the Earth Summit in Rio de Janeiro in 1992 [4, 5]. As the flip side of globalisation

* Corresponding author

regional and local entities have emerged as major drivers of political change in Europe [6]. These entities however have encompassing planning objectives that not only address the purely technological side of resource utilisation but also have to bring environmental and social aspects of innovations in line with economic considerations [7] and have to address issues of spatial planning, energy provision and use [8].

It is within this framework that innovation for sustainable regional energy systems has to be discussed. This requires a comprehensive set of planning tools that will be discussed and that will be elucidated in the case study offered in in this paper.

FRAMING THE PROBLEM

Providing solutions that allow regions to address their future role as major players in the game to provide society with energy and material resources requires a comprehensive approach to resource utilisation that also takes into account the inherent mechanisms of regional decision making. Renewable energy systems are characterised by highly complex interaction between actors from different sectors as well as long ranging decisions about the economic and social structure of regions and its impact on nature. Therefore decisions on the technological solutions to utilise regional resources have to be subjected to participatory planning processes involving all parties contributing and concerned by the final outcome. These planning processes by definition involve not only experts in the energy field but also providers of resources (e.g. farmers), grid operators, regional authorities and the citizens in the region that might be affected by changes in land use and energy provision as well as energy utilisation patterns. Rather than providing fixed technical solutions participatory planning requires the provision of sound, comprehensive and comparable scenarios that form the base of a discourse about the future of the region.

From a more technical point of view this requires to provide regional decision makers with the means to generate systemic structures for utilising regional resources optimally within the framework of available sources, existing economic and technical structure and demand in the region. Any planning approach that just builds on optimising single lines of resource utilisation (say optimising the use of wood) or focussing on single technologies (say biogas generation) will be insufficient to meet the planning goal of optimal resource utilisation in a region. Regions usually offer a variety of renewable resources and require meeting different demands like residential and industrial heat/cooling, electricity and mobility. This alone requires a technology system rather than optimising single technologies or the utilisation of single resources. On top of that efficiency in resource utilisation calls for interaction of technologies, where cascades of utilisation will offer higher value added on the same (limited) resource base.

Equally suboptimal are planning approaches looking for just meeting the demand within a region. Most energy forms (with the notable exception of thermal energy) are transportable and inter-regional distribution grids as well as transport pathways for concentrated energy carriers, gas and electricity exist in most regions. This subjects these energy forms to inter-regional and in many cases global market forces. It is within this inter-regional and global playing field that decision makers have to shape the future of their regions.

The task at hand for planning of renewable energy systems for regions is therefore to generate scenarios for utilisation networks that link resources, technologies, regional demand and inter-regional markets in a way that optimises the value generated for the region. This value however is not restricted to the economic aspect but also includes environmental sustainability as well as social and cultural aspects. Changing the boundary conditions of this optimisation like different land use regimes, different price structures for resources, products and services as well as taking into account competition between different uses of resources (e.g. between food and energy generation) will then lead to the decision support system needed in shaping future development in regions.

Looking at this problem from an engineering perspective, there are some aspects that can be supported by existing methods especially used in process engineering. The generation of regional technology networks is similar to the generation of optimal process networks, solved by process synthesis approaches. Both aim at generating a network of process steps that convert material and energy resources into valuable products where both resources and product demand may be limited and where different chains of process step may compete for the same resources, leading to similar products. Providing insight into the ecological pressure of regional technology networks is, at least on the metabolic level that takes into account mass and energy exchange with the environment, similar to the problem of environmental evaluation of industrial processes. It is therefore sensible to adapt the methods already well developed for process industry to the new task of providing decision support systems for regional renewable energy systems. It has to be reiterated at this point however that the results generated by these methods aim at providing scenarios for regional participatory planning rather than "optimal solutions" as they usually do in process industry.

ADAPTING PROCESS SYNTHESIS AND ECOLOGICAL PROCESS EVALUATION METHODS

There exist a wide variety of process synthesis and ecological process evaluation methods that can be adapted to the requirements of supporting planning for regional renewable energy systems. The current paper will discuss two particular methods and their adaptation and apply them to a case study.

Process network synthesis (PNS) using the P-graph method

The PNS method [9] has been successfully applied to develop optimal process networks for renewable resource utilisation processes [10-12]. This method derives maximum structures (encompassing all feasible structures fulfilling the given boundary conditions) via combinatorial rules using the bipartite graph representation of processes, arriving at optimal structures (that optimise a given target function e.g. value added generated by the process network) using a branch-and-bound optimisation routine. Besides short computation times this method has the advantage to securely find the optimum structure even for complex problems. This advantage is important in the application to regional renewable energy systems as it guarantees that all developed scenarios are actually optimal within their boundary conditions and therefore directly comparable. The method requires knowledge about the energy and material balance as well as economic parameters like operating costs, investment costs and depreciation periods for each technology included into the considerations.

A comprehensive description of the method is out of scope of the current paper; the reader is kindly referred to the original literature as well as to the very informative web-page of the PNS method [13]. The following paragraphs will be dedicated to the explanation of necessary changes and amendments to the method, if it is to be applied to regional renewable energy systems.

The main challenge by applying the PNS to regional energy systems lies in defining new "technologies" that play major roles in any resource-technology-demand network. This is in particular true for all activities within the primary sector like agriculture and forestry. Here we have one basic resource which is land. This resource is then the "input" to competing "primary technologies" i.e. different ways of land use which generate the material resources then utilised in energy technologies, be they crops, wood, grass also including residues like straw. Restrictions on land use to be considered are on the one hand climatic: not all crops may be grown in all regions. This is best handled by providing a regionally adapted set of primary technologies that generate the agricultural and forestry products amenable to the individual regional context. All these primary technologies have to be described in terms of their material and energy input (e.g. fertiliser and machinery use per hectare for a certain crop, yields per hectare and year) and their cost factors (cost of fertiliser, investment for farm equipment, etc.). Different agricultural practices (e.g. conventional and organic farming) can easily be integrated by changing the material and energy inventory as well as the prices of crops accordingly, leading not only to scenarios describing the most optimal land use but even giving decision support for the way the land is actually managed.

On the other hand there are restrictions regarding the land use as such as fields, grass land and forests are not interchangeable in regions without limitations and maintaining fertility in many cases requires crop rotation. This can be handled in partitioning the basic resource land into sub-resources such as fields, forests and grass land, each serving a particular set of primary technologies that generate the respective products, wood for forests, crops for fields and grass for grassland. Partitioning even further can be used to include crop rotation. If for instance oil seeds may only be grown every fourth year, it means that a fourth of the field area is open as a resource for the primary technology of growing oil seeds whereas the other land is not defined as a resource for this primary technology.

Finally energy technologies compete for products from primary technologies with other uses, most importantly the food sector. Therefore these products will also be assigned prices and a set of secondary technologies (e.g. husbandry, food processing) has to be included to decide between different pathways for utilising bio-resources. In many cases these technologies may also provide input to energy technologies (e.g. manure that may be used in biogas fermenters) further interlinking the maximum structure for regional applications of the PNS.

Besides including the primary sector regional renewable energy systems are critically dependent on logistics. Many biogenic resources, especially residues (e.g. straw) and wastes (manure) have dismal logistical properties like low transport densities and high water content. This means that transport is a major factor in the design of regional technology networks and has to be factored into the decision about the optimal sizes of energy provision technologies. This may be accomplished by implementing transport as intermediate technologies between biogenic resources (as products from primary technologies and/or technologies from the food sector) and different sizes of energy technologies: smaller size technologies may then be served by (local) tractor transport over a mean distance defined by regional context, installations with larger capacities require transport via road or rail according to the mean distance to their resource base, which again is dependent on regional context.

Providing heat (or cooling) for industry and residential areas is always a major factor of regional energy systems that has to be integrated into any synthesis of technology networks. This factor has two aspects: on the one hand energy provision here competes with energy saving measures and on the other hand thermal energy may only be transported over short distances via heat/cooling distribution grids. The former may be tackled by introducing “efficiency technologies” like insulating buildings. These technologies “provide” the energy difference between the situation in status quo and a situation when the optimised technology network is implemented. Investment cost, operating cost (if applicable) and material balance for these technologies, as well as energy saving per unit of technology (e.g. kilogram of insulation) have to be defined. The latter may be given for different applications (e.g. buildings of different standards).

The particular logistic property of thermal energy that it can only be feasibly transported over relatively short distances by heat/cooling distribution grids has to be factored in by indicating the heat/cooling load that might be covered by district heating/cooling. This thermal load may then be supplied either by central heating/cooling installations or by off-heat from Combined Heat and Power (CHP) plants or by excess heat from industrial plants. Conversely high temperature process heat may either be provided directly or as excess heat from CHP plants.

Another important feature of the PNS method is the possibility to balance production with demand. This is particularly useful for implementing boundary conditions often asked for by regional actors: to guarantee supply of certain goods (e.g. food) or services (e.g. residential heating) from local resources.

The Sustainable Process Index (SPI)

This index describes the aggregated ecological pressure of a certain process by the area needed to embed this process sustainably into the ecosphere, rendering a kind of "ecological footprint". The SPI identifies the area A_{tot} necessary to embed a life cycle providing a certain goods or service sustainably into the ecosphere. The life cycle comprises all activities from raw material generation to the final conversion and, when applicable, end use of a product. A_{tot} is calculated according to

$$A_{tot} = A_R + A_E + A_I + A_S + A_P \quad (1)$$

The areas on the right hand side are called "partial areas" and refer to impacts of different productive aspects. A_R, the area required for the production of raw materials. A_E is the area necessary to provide energy. A_I, the area to provide the installation for the process, A_S is the area required for the staff and A_P is the area for sustainable dissipation of products and by-products. The reference period for these partial areas is one year. All material flows and energy flows exchanged between the life cycle to provide a good or service in question and the environment will give raise to an according area under the categories identified above. The SPI method is based on the comparison of natural flows with the flows generated by a technological process. The conversion of mass and energy flows into area is based on two general "sustainability principles":

Principle 1: Anthropogenic mass flows must not alter global material cycles; as in most global cycles (like the carbon cycle) the flow to long term storage compartments is the rate defining step of these dynamic global systems, flows induced by human activities must be scaled against these flows to long term stores.

Principle 2: Anthropogenic mass flows must not alter the quality of local environmental compartments; here the SPI method defines maximum allowable flows to the environment based on the natural (existing) qualities of the compartments and their replenishment rate per unit of area.

Whenever a life cycle produces more than one product or service (e.g. in CHP technologies where heat, electricity and material products like manure from biogas plants or ash from incineration are produced) ecological pressures have to be allocated to them according to an allocation rule. In this case study ecological pressures were allocated to all products produced in the region. Allocation was based on the income calculated at market prices.

The SPI already draws on an extensive data base concerning energy and efficiency technologies that is accessible on the web page [13] or from previous work [14, 15]. A particular tool for evaluating the impact of primary sector technologies was recently developed and is accessible via [16].

The advantage of using the SPI method for evaluating regional renewable energy systems is twofold: on the one hand this measure offers a comprehensive, life cycle wide evaluation that rates very distinct impact like CO_2 and heavy metals emissions on an aggregate level, allowing for comparison on the base of sound sustainability principles. On the other hand the SPI clearly distinguishes between renewable and fossil resource based technologies which is of high importance to regional actors.

CASE STUDY MÜHLVIERTEL

The case study will provide insight into the application of the methods described above in a real world development process on the regional level in Austria. The task at hand was to provide regional decision makers with a reliable base for deciding about the future pathway to utilise their renewable resources and restructure their energy system in order to reduce the overall ecological pressure.

The region in question is the Mühlviertel, a region spanning from the Danube to the German and Czech boarder, close to Linz, the capital of the federal state Upper Austria. The region encompasses 3,080 km² with a population of approx. 268,000 citizens. It is a highly agricultural region with particularly strong emphasis on grass land and forestry.

In co-operation with regional actors three main scenarios were defined:

- Optimal scenario: maximum value added for the region;
- Autarky scenario: total autarky for food and energy;
- Supply Linz scenario: optimal value added with responsibility to keep supply of food for the urban centre of Linz slightly above current levels.

Based on the climatic situation of the Mühlviertel and in consultation with local experts a list of possible agricultural products, their yields and limitations was defined. The current status and number of buildings as well as information about existing energy installations, waste flows and industrial energy demand was collected from a survey among all involved communities. In consultation with decision makers in the region the list of eligible technologies was defined, using a conservative approach by including only technologies that are either already state of the art or proven in industrial size demonstration plants such as the “Green Biorefinery”, a technology that uses pressed juice from silage to obtain amino acids and lactic acid [17]. Together, all render a maximum structure employing the PNS method as given in Figure 1.

By setting the demand according to the boundary conditions of the scenarios and using market prices for all products and services (if not stated otherwise in the explanation of the scenarios below), the three scenarios were then calculated using the PNS editor from the homepage given above. The definition of all boundary conditions and technology parameters is however out of scope for the current paper. The interested reader is kindly referred to the end report of the project [18]. The following paragraphs will be dedicated to describe the results of these calculations as well as the ecological implications revealed by the evaluation with the SPI.

Optimal scenario 1

The boundary conditions for the optimal scenario resulted in two almost equally attractive structures for the regional technology system:

- A “biogas fuel” scenario (scenario 1A);
- “High price beef” scenario (scenario 1B).

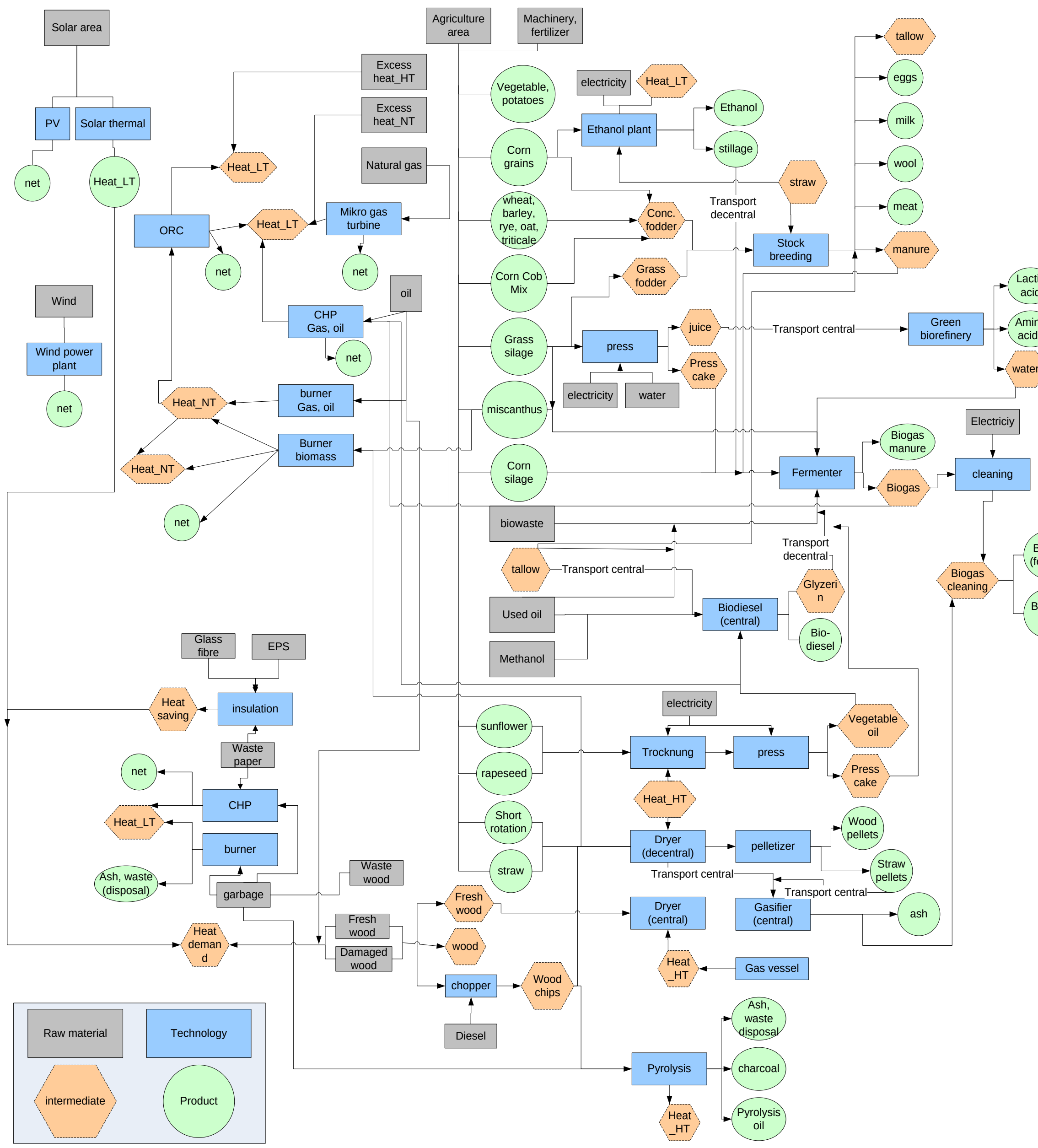

Figure 1. Maximum structure for the Mühlviertel case study

If the price for biogas is set to a level currently paid for as fuel (65 €/MWh), almost the whole grassland is used to provide input for biogas fermenters. Silage is produced from grass, then pressed, with the juice going to the green bio-refinery and the press cake is utilised in biogas fermenters. The biogas is then cleaned and fed in the grid to be distributed to fuel stations within and outside the region. Fields are mainly used to support (organic) pork breeding, with most of the pork being exported out of the region. Vegetables for regional consumption are also grown on the fields.

Almost as much added value can be achieved for the region if beef is produced with organic farming and the price for this product will be in the upper range for high quality meat (4,030 €/t). In this case grassland will be used to support cattle breeding. Manure is collected as much as possible and processed in biogas fermenters, again cleaned and fed to the grid. This scenario however has lower biogas production and no production of chemicals from the Green Biorefinery. Fields support mostly cattle breeding, with the remainder going to organic pork breeding and vegetable production for regional consumption.

Both scenarios use the available forest products for provision of residential heating as well as process heat. Wherever possible district heating based on wood chips is preferred, with firewood furnaces supplying houses outside the range of district heating distribution grids. Buildings are insulated as much as possible. All waste wood and a small portion of fresh wood are utilised in pyrolysis plants, generating oil that is subsequently refined into bio-fuel. Fat from slaughterhouses is also processed to bio-diesel in both scenarios. Wind-power, hydro power and photovoltaic are utilised to capacity which means in the case of PV a steep increase of installed area, up to 30 fold the amount used currently.

Autarky scenario 2

Autarky requires a different strategy as all food and energy have to be produced in the region. In this scenario heat for individual buildings outside the range of district heating grids is again provided mostly by wood, but here material utilisation of wood for regional construction is competing for this resource. Grassland supplies, besides the necessary amounts for cattle breeding and milk cows, biogas fermenters, with silage juice going to the Green Biorefinery although at reduced rates compared to the scenario 1A (as much silage goes to husbandry). Biogas is used for CHP, generating electricity for regional consumption (which can be covered if photovoltaic, wind power and hydro power are utilised to capacity). Part of the biogas is again cleaned and used for transport fuel however this part is considerably lower than in scenario 1A. District heating uses excess heat from these CHP-plants with the shortfall filled by using miscanthus grown on fields in heating plants. Food for regional consumption can be supplied by local agriculture.

The use of waste wood, fat from slaughtering is the same as in the optimum scenarios, buildings again are insulated as much as possible. Transport fuel however cannot be supplied in an amount to meet transport needs at the current level.

Supplying Linz scenario 3

Supplying the urban centre of Linz with food (cereals as well as meat) at a slightly higher level than today of course requires land that is then not available for either energy resources or other ways of utilisation that increase the added value in the region. Although regional heat demand can be met by using wood and employing insulation to increase energy efficiency of buildings, neither electricity demand nor transport energy can then be supplied in the amount to meet current levels of consumption. In general this scenario calls for a similar technological structure like scenario 1A, albeit with lower capacities for biogas fermenters and Green Biorefineries as fewer resources may be allocated to energy and industrial use.

COMPARING SCENARIOS

The scenarios differ regarding the supply of energy for the region. Heat demand can always be met; however transport and electricity demand vary in their degree of regional supply as shown in Figure 2.

Regarding the economic parameters the scenarios differ widely, especially with respect to the ratio between investment and revenue. Figure 3 shows this for all scenarios.

Figure 3 shows that scenario 1B shows a slightly lower revenue than 1A (roughly 3%) however needs 16% less investment. Autarky requires almost the same investment as the optimal technology network however achieves only 63% of the revenue. Supplying a major urban centre with food decreases revenue dramatically, to below 60% of the optimum level. This scenario however also requires the lowest investment with only 70% the amount necessary for the optimum scenario.

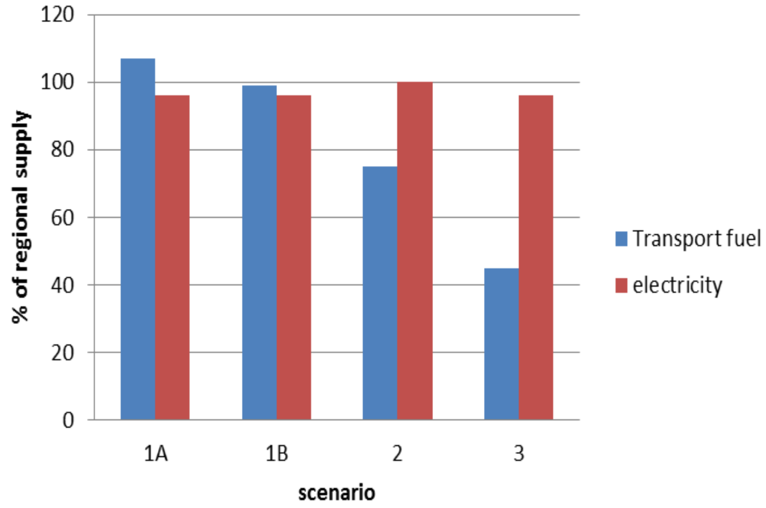

Figure 2. Regional coverage of transport and electricity demand in the scenarios

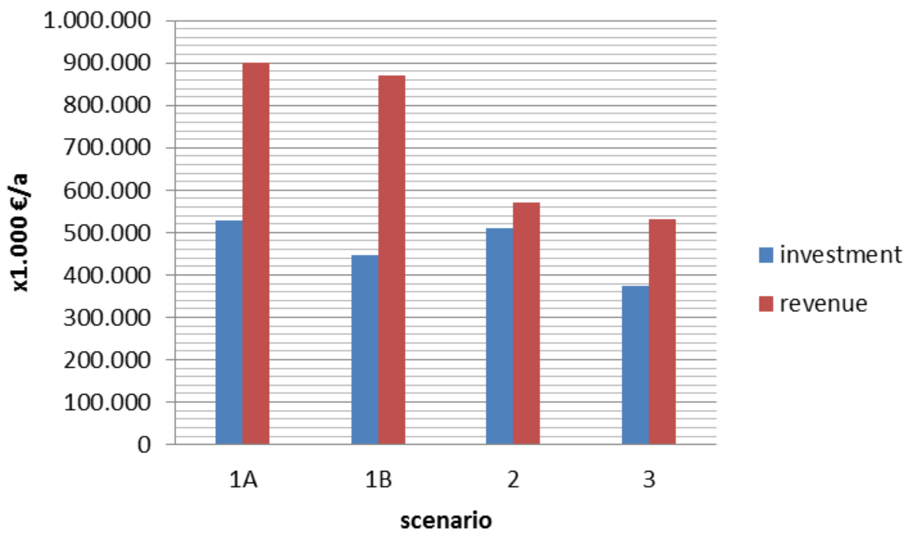

Figure 3. Investment (annualised with 10 years depreciation time) and yearly revenue for all scenarios

Concerning the ecological pressure, all scenarios presented here are reducing the ecological footprint against the status quo considerably as Figure 4 shows. This figure also shows the reduction in the ecological footprint for providing energy in the different scenarios using the different technological pathways defined by PNS optimisation.

Figure 4 shows that as all scenarios change the energy system of the region mostly towards renewable resources, overall ecological pressure of the region is reduced to a third (scenario 1 and 3) and even a quarter (scenario 2). All energy services provided by regional resources show massively reduced ecological footprints, with heat at only 20 % of the current status in all scenarios. The differences in the footprint of fuel are mostly due to the percentage of cleaned biogas used in the scenario, with scenario 1A showing a relatively high (but still much reduced) footprint for this energy form. By and large, autarky shows low ecological footprints. That has to be contrasted with the low economic performance of this scenario.

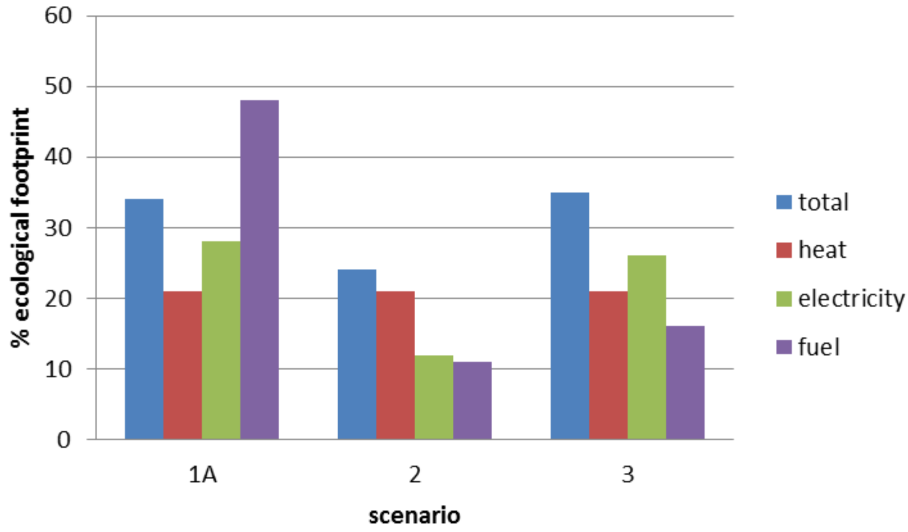

Figure 4: Comparison of ecological pressures using the SPI evaluation of all scenarios against the status quo (footprint for energy referring only to regional provision)

What regional decision makers can learn

As stated earlier, applying PNS and SPI to regional renewable energy systems must be seen in the context of encompassing decisions about the future of regions. The scenarios presented here (which are only a fraction of the scenarios calculated in this process) delimit the decision space for the development of this region and provide insight into the choices as well as stable elements of any future technology structure based on regional resources.

First stable elements that show up in every scenario can be analysed:

- Wood will become the base for heat provision in the region; this means that all measures to mobilise wood resources and establish energy logistics for wood are safe decisions for the region;
- District heating should be developed to capacity;
- PV as well as wind and hydro power should be developed to capacity;
- Insulating all buildings to low energy standards is necessary to gain energy efficiency;
- Biogas mobility shows great potential in all scenarios; this means that logistics for this form of fuel as well as measures to increase the car fleet that may use bio-methane as fuel are safe decisions for the future.

As interesting as the stable elements are the stark choices that the scenarios reveal. Amazingly enough, the future of the Mühlviertel critically depends on the utilisation of grassland and only to a minor degree on all other land resources. There is a choice to orient the region towards energy export and industrial utilisation of renewable resources (scenario 1A) or intensify marketing of existing agricultural products, in particular beef (scenario 1B). Both require major efforts to open new markets and to build up the necessary infrastructure and marketing structure. Whereas a focus on energy and industrial utilisation promises the highest revenues it also requires the highest investment.

Autarky as well as supply of a nearby urban centre will diminish revenue for the region considerably. Autarky in particular couples low revenues with high investment requirements.

All scenarios show much lower ecological pressures than the status quo, with the lowest overall environmental impact exerted by autarky. The environmental pressure for heat will be reduced to a fifth of the current level and stays relatively constant in all scenarios as the way heat is provided is stable throughout the scenarios. Both fuel and electricity footprints vary considerably, depending on the different pathways for their provision associated with the scenarios.

CONCLUSION

Regions will become major decision levels for the energy change necessary in the 21st century. As regional resources as well as demands are quite diverse, technological solutions will have to be adapted to the individual regional context. Utilising renewable resources to gain maximum regional revenue while exerting minimum ecological pressure will always require technological systems rather than single technologies, taking into account the framework and boundary conditions resulting from the ecological, logistical, economical and societal aspects of utilising renewable resources as discussed in this paper.

Implementation of radically new technological systems that entail major changes in business models and logistics require careful and participatory planning processes involving actors that have in many cases not co-operated before. This needs efficient tools that allow for systemic optimisation while providing insights into the long term choices to be taken. Adapting process synthesis and ecological process evaluation to the regional case can help to provide decision makers with comparable scenarios that will guide the planning process.

The case study shows that these tools will lead to a much clearer picture about the specific challenges for regional development when introducing renewable energy systems. It also shows clearly that using regional renewable resources lead to considerable chances for increasing regional revenue while cutting ecological impact dramatically.

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