Optimisation of Regional Energy Systems Centred on Wastewater Treatment Plants

This article discusses local energy systems centred on wastewater treatment plants, optimised by Process Network Synthesis and evaluated ecologically by the Sustainable Process Index.

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Abstract

In addition to the treatment of wastewater, sewage treatment plants are able to generate energy. On the one hand the energy can be used to cover the in-house demand of the plant and on the other hand surplus energy can be integrated in the local energy system. This article describes the basic ideas of the methodologies being used to detect the best economic and ecological way to distribute the available energy. The economic optimisation of the energy system is performed by the Process Network Synthesis (PNS) and the ecological evaluation by the Sustainable Process Index (SPI). Furthermore the article contains a description of a real life case study.

Introduction

An answer to global warming can be to focus on the regional use of renewable resources. Using the infrastructure of an existing wastewater treatment plant for generating energy out of wasted local resources, e.g. the wastewater itself or sewage sludge and gas, can help provide energy in a sustainable way. This is not only helping the climate, it also can also be economically reasonable. This sustainable approach is discussed in this article.

Methods

Process-network synthesis (PNS)

The Process Network Synthesis is an optimisation tool (Friedler et al.; 1992) which may include different technical, environmental, economic and social constraints. It is realised in the software package PNS Studio. Originally the PNS was developed to design chemical processes but it is also suitable to construct and analyse structural alternatives for supply chains (Kalauz et al., 2012), therefore it is applied for the energy supply of wastewater treatment plants in this case study.

The base of a network synthesis is a set of specifications. These specifications consist of the definition of materials, operating units and products. The maximum structure which includes all feasible structures of technologies for the process system is then generated using combinatorial rules. Out of these possibilities the PNS finds optimal structures for a given problem (Friedler et al.; 1992).

To generate the maximum structure for a case study with PNS Studio certain types of information need to be obtained, evaluated and specified. The procedure is as follows:

Step 1: Specification of materials.

The specification of materials involves the differentiation of raw materials and intermediate materials. Raw materials are defined by their type and price. There may also be defined a required as well as a maximum flow. The price for materials follows the convention: If the system has to pay for materials they are assigned positive prices. Intermediate materials are only defined by their type. The amount of intermediates is determined by the calculation.

Key messages:

- Optimising the internal and external energy flows at wastewater treatment plants requires economic and ecologic considerations.
- Process Network Synthesis (PNS) can be used for economic optimisation, whereas the Sustainable Process Index (SPI) can be used for ecological evaluation.
- The concepts are demonstrated using the case study of a wastewater treatment plant treating wastewater of 30‘000 persons

Step 2: Specification of operating units.
Operating units (technologies) need to be specified by their in- and output flows (materials and energy) as well as investment and operating costs. If technologies already exist, investment costs are not considered. Upper and lower boundaries can be set to limit the capacity of technologies.

Step 3: Specification of products.
Products need to be classified in the same level of detail as materials: type, price and optional a required as well as a maximum flow. There is also a sign convention for products as it is for materials. If it is waste with fee-based disposal their price is negative.

In the case of dealing with wastewater treatment plants additional aspects have to be taken in account:

- Time dependent load and provision: A multi-period model to depict dependences like resource availability (e.g. sun for photovoltaic installations) or product demand (e.g. heat). In this study the year is divided into the following three periods:

  Winter: 1 December – 31 March
  Midterm: 1 April – 31 May plus 1 Oct – 30 Nov
  Summer: 1 June – 30 September

- A static economic depreciation is used with pre-defined operating time spans for different technologies/installations.
- A maximal operating time of 8000 h/y is considered, actual operating times may be subjected to multi-periods optimisation.
- Technologies with different capacities are implemented to take economy of scale into account. This means the PNS can choose e.g. between heat pumps with 660 kW, 460 kW or 210kW heat output.

The maximum structure of a wastewater treatment plant is displayed in Figure 1.

PNS Studio applies an accelerated branch-and-bound (ABB) mathematical optimisation algorithm to find the optimal structure. This algorithm progresses from the product level through the maximum structure up to the raw material level. At each branch the algorithm decides which operating unit should produce a predefined material (Varga et al., 2010). If the optimisation target function is economic, the aim is to identify the least expensive solution structure or to develop the profit to a maximum (Figure 2) (Süle et al.; 2011). The ABB algorithm has, compared to general solvers, one major advantage: in addition to the generations of a global optimum it also generates the n-best suboptimal structures. The variable n is given by the user (Bertok et al., 2013). This allows comparison between feasible structures.

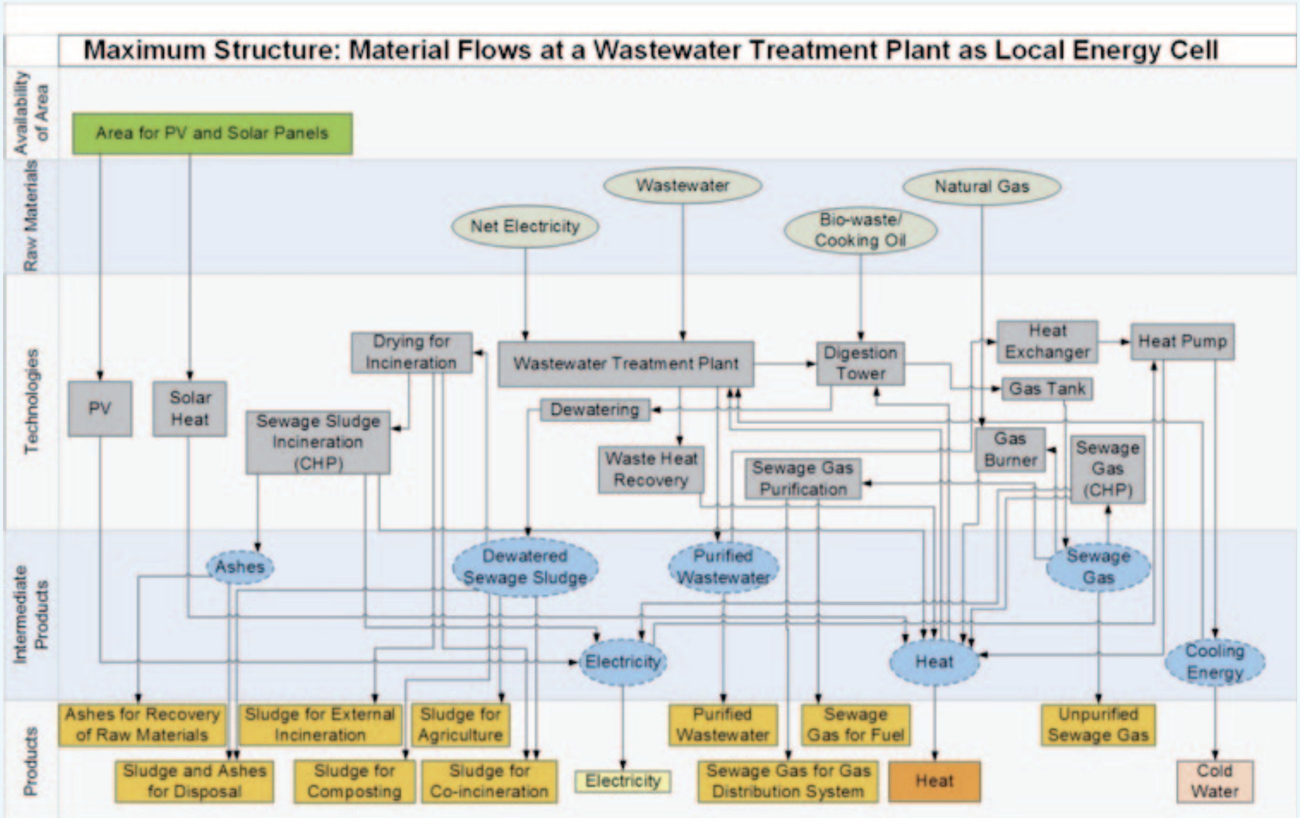

Figure 1: Maximum structure of a wastewater treatment plant with digestion

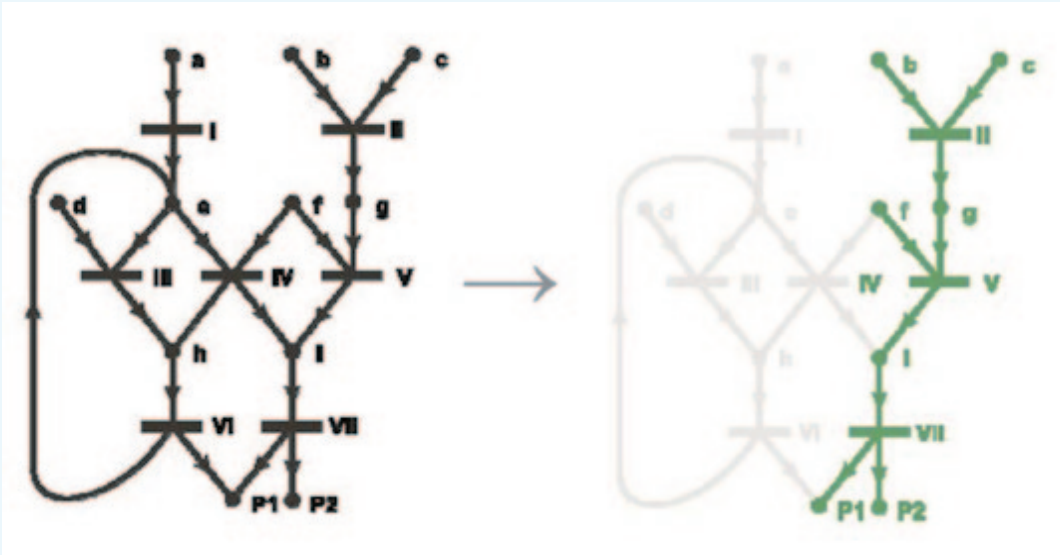

Figure 2: From a maximum structure to an optimum structure (Friedler et al. 1995 adapted)

Sustainable Process Index (SPI)

The Sustainable Process Index (SPI) is a member of the ecological footprint family. It is compatible with the procedure of the life cycle analyses (LCA) described in the EN ISO 14040 (ISO, 2006). Ecological footprints are indicators based on the principle of strong sustainability. They measure human demand for natural income for different production processes and services like food production, mobility, waste disposal, etc. and compare it with Earths capacity to convert natural income (in the form of solar radiation). The Sustainable Process Index follows this approach for the evaluation of environmental impacts of processes, products and services.

The SPI is calculated using material and energy flows extracted from and dissipated to the ecosphere and compares them to natural flows (Krotscheck and Narodoslawsky, 1996). Two main principles govern the calculation to integrate human activities into the ecosphere in a sustainable way:

- Human activities are neither allowed to change the quality nor the quantity of natural material cycles in the long run, e.g. the carbon or nitrogen cycle
- Anthropogenic changes of material flows in and out of the compartment air, soil and water must not exceed the natural variations in quality or quantity

For the comparison between human induced and natural flows, SPI uses the following data for natural systems: sedimentation rate of carbon in oceans, natural concentrations of substances in soil and water, the exchange rates per area unit of volatile substances between forests and atmosphere as well as the local renewal rates for soil and water (Kettl, 2013).

The SPI calculates the ecological footprint from the following partial areas as shown in Figure 3:

- Direct area consumption for infrastructure
- Area consumption for provision of non-renewable resources
- Area consumption for provision of renewable resources
- Area consumption for dissipation/sedimentation fossil carbon
- Area consumption for dissipation of emissions in water
- Area consumption for dissipation of emissions in the soil
- Area consumption for dissipation of emissions in the air

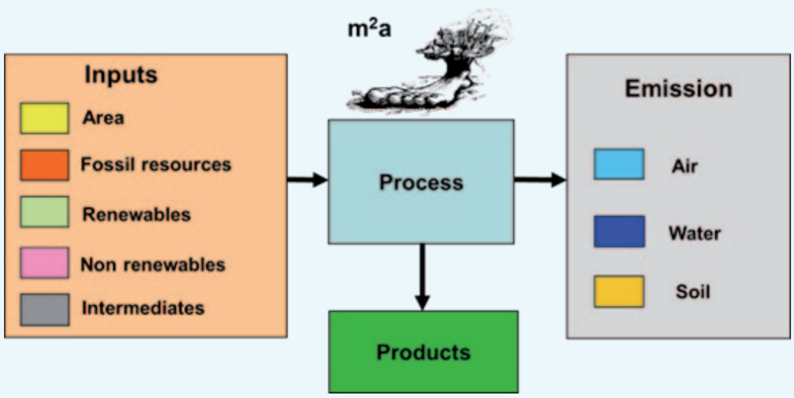

Figure 3: SPI calculation, input and emission flows of a process (SPIonWeb, 2014)

The main advantage of the SPI is the possibility to compare different environmental pressures caused by processes by converting them to one unit, namely area [m²]. In particular it can compare fossil based processes with those on a renewable resource base.

SPIonWeb

For a fast calculation of the Sustainable Process Index a web based software tool SPIonWeb, has been developed at the University of Technology in Graz. This tool is available on http://spionweb.tugraz.at/ as free ware. SPIonWeb can assemble whole life cycles through process chains and process cycles, based on the mass and energy balances of the process. A main database, including processes e.g. for energy production, mobility, chemicals and base substances is implemented in the tool. This helps the user to build life cycles from raw materials to end products (or services) by using existing building blocks. The idea is that users are be able to evaluate the whole life cycle and calculate as results their SPI Footprint, CO_2-life-cycle-emissions and Global Worming Potential (GWP) based on the ecological inventory of just the process he focusses on, using database processes for the pre-chain. These results can help the user to find the most environmentally friendly solution when it comes to production or offering services (Kettl , 2013).

Further information on SPI and different ecological footprint calculators is available on http://www.fussabdrucksrechner.at.

Case Study

For the current research project three Austrian wastewater treatment plants were selected to represent the different roles of a plant as a local energy cell. These roles depend on the size of the plant as well as the geographical context e.g. possible energy consumers. The case studies are focusing on an economic optimisation of the energy system centred on wastewater treatment plants with PNS Studio. In addition to that, an ecological evaluation, using the SPI methods will be performed. The aim is to cover the in-house heat demand of the plant and to supply local energy systems with energy in an economic and ecological way.

In this article the first steps regarding the case study of a city with 7500 inhabitants in the Austrian province of Upper Austria is briefly explained. The wastewater treatment plant corresponds to a population equivalent of 30000. First of all local stakeholders like economic, social, political and administrative actors were informed in a workshop about the project. In an ensuing discussion conceivable energy customers and future energy demands have been defined. The heat supply of a local hospital and an industrial area, which is planned to be built in the vicinity of the wastewater

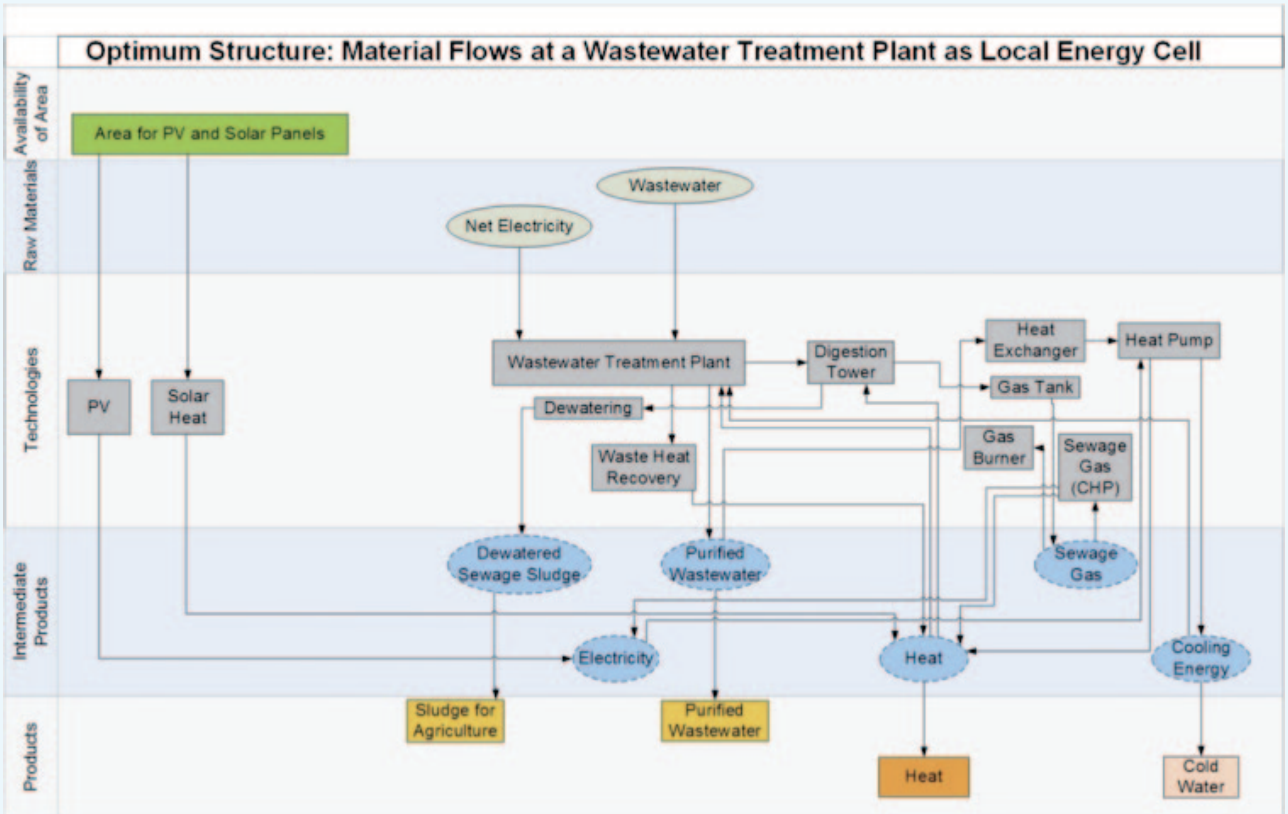

Figure 4: Example for an optimum structure of a wastewater treatment plant focused on the heat supply in a scenario under current economic conditions

treatment plant, were identified as options by the stakeholders.

The case study is still an on-going project. For the economic optimisation it is not clear yet which heat energy price can be achieved. For this reason a sensitivity analysis on the heat price with PNS Studio was realised. The largest possible amount of heat with the available technologies is produced according to Figure 4.

Having the sensitivity analysis in mind less heat producing technologies were chosen by the PNS and the amount of heat output decreases as well if the prices for the produced heat are decreasing.

Currently discussions with all relevant stakeholders about useful technologies and the achievable heat energy price in the particular region are ongoing. Once a price is specified the optimum economic system will be calculated and the selected technologies will be evaluated in an ecological way.

Conclusion

It seems likely for this case study to supply the in-house heat demand of the plant itself in a more economical and ecological way. Industrial and residential areas nearby may benefit from an integrated and optimised energy system centred on the sewage plant as local heat provider. The investigation of the centred energy systems will help the operator, political decision makers in the region and other stakeholders to utilise the potential of energy supply for the sewage plant and its surrounding areas in the future.

Acknowledgement

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