Urban production: smart rooftop greenhouses on factories

Dipl.-Ing. Martin Reisinger
EEP – Institute for Energy Efficiency in Production
Fraunhofer Institute for Manufacturing Engineering and Automation IPA
Nobelstr. 12
D-70569 Stuttgart
Germany
martin.reisinger@eep.uni-stuttgart.de
martin.reisinger@ipa.fraunhofer.de

Prof. Dr.-Ing. Dipl.-Kfm. Alexander Sauer
EEP – Institute for Energy Efficiency in Production
Fraunhofer Institute for Manufacturing Engineering and Automation IPA
Nobelstr. 12
D-70569 Stuttgart
Germany
alexander.sauer@eep.uni-stuttgart.de
alexander.sauer@ipa.fraunhofer.de

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Abstract

One approach to increase energy efficiency and energy flexibility of production systems is to connect independent production systems and local supply systems to energy networks. One technology that can be adopted is smart rooftop greenhouses (SRG). The main subject matter of a SRG is the energy symbioses through waste heat usage and smart grid integration to improve energy efficiency of a production system.

With a SRG on a factory the waste heat and CO_2-emissions can be used for plant production. As a SRG can be heated with low temperature waste heat, a big energy efficiency potential in the German industry can be addressed. Furthermore, this allows for space to be used more efficiently for supporting land-use reduction goals. The connection and integration of a SRG in the industrial smart grid brings in further flexibility for its energy optimal control. With a highly automated and digitalized plant production technology in a controlled environment agricultural system like an SRG, the production of bio-based production materials or food can be automated and optimized.

The aim of this publication is to present a concept for smart rooftop greenhouses. Therefore the paper is supported through a systematic literature review on the subject. The results of this review have been combined and further developed with new approaches.

Introduction

Energy and resource efficiency does not have to stop at the factory gates. Industrial ecology is a research field for holistically optimizing energy a resource efficiency. This field of research studies energy and material flows through industrial systems (Ehrenfeld 1997). Energy-related planning and technological solutions go beyond the borders of a production plant by extending the framework to include the environment in the energy optimization process. The goal is to create energy and resource symbiosis between production processes and integrating them into local supply systems. Industrial ecology is an approach for the transition from a fossil fuel powered linear economical system to a more sustainable circular low-carbon economy.

The urban production concept (Lentes 2016), for example in the form of ultra-efficient factories, can be assigned to the research field industrial ecology. The ultra-efficient factory is a new paradigm for industrial production. The paradigm aims to optimises the positive impacts of manufacturing to its surroundings instead of only minimising negative influences (Lentes et al. 2017).

In this paper, the concept of a SRG is introduced. The SRG concept combines the idea of urban production and the ultra-efficient factory with concepts of urban agriculture in the form of rooftop greenhouses. Research results show that urban farming concepts like rooftop greenhouses can be an option for increasing energy efficiency in an urban context (Sanyé-Mengual 2015). Other forms of urban agriculture, like vertical farming which can be described as indoor farming in buildings (Despommier 2010), is at the current technological level using more energy for production than comparable conventional production methods (Podmirseg 2015).

The Smart Rooftop Greenhouses concept

SRG presented in this paper is based on a literature review extended with new approaches. The main subject matter of the concept is the energy symbioses of waste heat usage and smart grid integration to improve energy efficiency of a production system.

The SRG concept is an approach for the evolution of existing greenhouse technology through a digitalized and automated combined industrial and biological production process. This enables an energy and resource symbiosis and a biological carbon sink for emissions from manufacturing processes.

An overview of the SRG concept is given in Figure 1. The components are described in the text below. The literature review, which the concept is based on, and further description elements are summed up in the sub chapters below.

The basic constructional element is the greenhouse (No. 1) on the rooftop and the facade of the factory. Within the maximally transparent greenhouse the climate is controlled for optimal plant production. Through a modular design of the greenhouse, with different climate and lightning zones, the SRG can produce different species of plants. With the facade module, southwards facing facades can also be used for plant production. The facade module can be, for example, a glassed construction with integrated cultivation technology or a green wall for reducing the thermal load of the factory.

The main subject matter is the energy symbiosis (No. 2) between the factory and the greenhouse. The first central symbiotic element is the use of the waste heat from manufacturing processes in the factory. In addition to this element, the low temperature waste heat from the exhaust of combined heat and power units (CHP) can be directly used for heating and CO_2 fertilization of the SRG. This enables to use energy very efficient through an exergy cascade. In the cascade high temperature CHP process heat is used for the manufacturing process and the low temperature waste heat from the manufacturing process as well as from the CHP flue gas is used for thermal conditioning of the SRG. The second element is the integration of the greenhouse in the smart grid. The aim is to deliver energy flexibility to energy systems with a high share of variable renewable energy from wind power and solar power. This flexibility is for example based on power-to-heat technology, flexible CHP capacity and time flexible artificial lighting for plant production. The energetic symbiosis of the SRG can be controlled and optimized by incorporating all energy generation, storage and consumption components from the production system into a micro-grid. Either the micro-grid is an independent off grid solution or it is a prosumer which also consumes and produces energy through the local smart grid cell from the upstream power distribution network.

The plant production (No. 3) in the greenhouse can deliver bio-based manufacturing material, food for the smart factory's canteen and the consumers in the urban surrounding areas or indoor plants, for example for offices.

Smart plant production systems can be developed through the transfer of the automation and digitalization technology (No. 4) from the manufacturing processes in the factory to the plant production system. Combined further research and development enables the use of biologically based optimization approaches in both systems. For example through using sensing technologies and image processing developed for manufacturing systems for optimal plant care. Plant production and picking is highly automated with robot technology while plant packaging and meal preprocessing is realized through highly automated technology.

ROOFTOP GREENHOUSE (NO. 1)

A greenhouse is a form of controlled-environment agriculture, providing optimal growing conditions for species (FAO 2013). In the course of the development of urban agriculture solutions conventional greenhouse technology is undergoing an evolution (Vogel 2008) and therefore, the SRG concept can be considered as one possible element of this evolution.

Industry and commercial facilities often have a high, and aside from photovoltaics, unused space potential on rooftops, facades and parking and logistics areas. Rooftop greenhouses use this wasted roof space. This enables space efficiency through the double usage of this space for manufacturing and plant production and therefore excessive land use is limited. This is important, as land consumption for settlement and infrastructure is growing. For example, in Germany the land consumption objective of the Federal Government of Germany is to limit the land consumption within the country to 30 ha per day. Currently the land consumption is twice as big as the objective (Statistisches Bundesamt 2016) (Malburg-Graf et al. 2007).

However, there can be a potential conflict over the utilisation of the rooftops between a rooftop greenhouse and photovoltaics (Sanyé-Mengual 2015). Innovative photovoltaics technology enables a combination of both forms of usage. Plants use only parts of the electromagnetic spectrum of the sun's radiation for photosynthesis. This part is called the photosynthetic active radiation (PAR). The non-PAR can be used for power generation with semi-transparent photovoltaics (Bambara and Athienitis 2015) , for example with luminescent organic photovoltaics technology (Corrado et al. 2016).

The SRG lowers the heat transmission through the building envelope from the factory. This lowers the heating and cooling demands. For example by combining the SRG with an evaporation cooler and integrating this system in the space conditioning facility of the building, the cooling demand in summer can be reduced (Nelkin et. al. 2007).

ENERGY SYMBIOSIS (NO. 2)

The energy symbiosis consists of two elements. The waste heat usage and the smart grid integration of the SRG. These elements are described in the following subchapters.

Waste Heat

The SRG concept focuses on waste heat usage from industry. In Germany there is a huge untapped energy efficiency potential (Sauer et. al. 2016) through the use of waste heat. In industry not all waste heat can be reintegrated into the company's production processes. So an energy symbiosis, with a SRG for plant production as a new nearby heat sink can be an effective technical solution for the use of waste heat. Exegetically optimized waste heat systems enable optimal energy use (Hertle et al. 2016) and can, therefore, contribute to the CO_2-mitigation targets in the Paris Agreement (UNFCCC 2015). Of course, there are other technical solutions for using waste heat – for

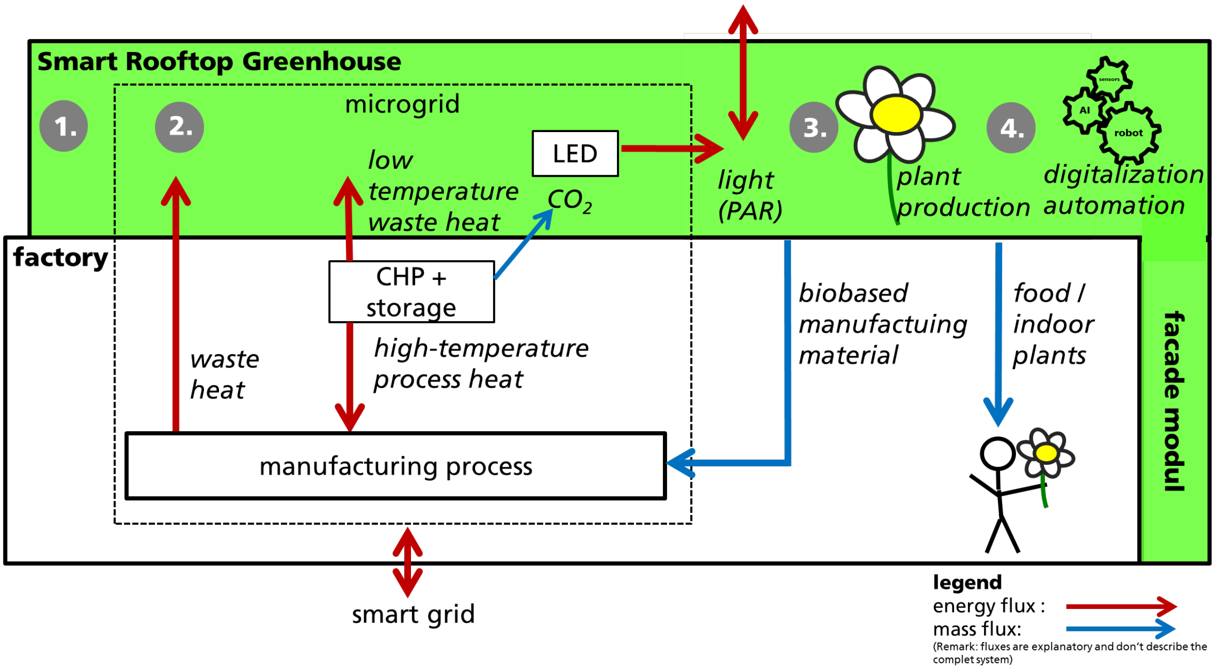

Figure 1. SRG concept – technical conception of resource and energy symbiosis. The numbers enable the referencing of the following sub-chapters.

example heat networks – but a comparison of SRGs to these technologies is out of the scope of this paper.

Using waste heat for heating greenhouses, for example from nuclear plants (Olszewski 1979), from industrial processes (Pearce et. al. 2011) (Sommarin et. al. 2016), from solar photovoltaic production (Pearce 2008) or from data centers (Fiore 2012), has been a topic of research for decades.

For this kind of projects, the general barriers for waste heat usage can be considered. The main barrier project finance (Schnitzer 2012) as they are very capital intensive with much higher payback periods (Krause et al. 2015) than usually common in industry. Besides the capital intensive waste heat usage technology, one significant cost component is the high transaction cost through complex contractual and regulatory arrangements for energy delivery. Therefore, further research should, ideally, also address the development of innovative business models.

A possible solution for this non-SRG specific issue could be an intermediary for the energy symbiosis between the companies. This intermediary could deliver controlled environments in terms of temperature, humidity and photosynthetically active radiation (PAR) through artificial lighting in the SRG. The second biggest barrier is, that there is no heat demand in physical proximity of the waste heat source (Schnitzer 2012). Obviously SRGs can be a solution to this barrier.

No research could be identified for integrating the heat demand form greenhouses in heat networks for compensating decreasing heat demand due to deep energetic retrofitting of to the network connected buildings. SRGs could also be an option for optimal energy usage in heat networks through using the low temperature return flow of heating networks.

The first large scale coupling of waste heat from energy production with greenhouses can be observed in the Netherlands, which can be considered as the market leader in high tech greenhouse technology and in horticulture (nuffic 2013). Based on fast CHP technology diffusion (van der Veen et. al. 2015), the sector now produces crops as well as energy. Feeding the flue gas from gas engine CHP directly into the greenhouses enables the use of low temperature waste heat in the flue gas for heating the greenhouse. The CO_2 in the flue gas is used for fertilization in the greenhouses. The high temperature heat from CHP is also mainly used for heating the greenhouse. Through installing higher thermal CHP capacities than needed for heating the greenhouse and combining the CHP with heat storage solutions, the CHP can deliver flexible power to the grid. The CHPs in the sector have an installed capacity of 3.1 GW_{el} and deliver flexible excess power to the energy market. This installed capacity is higher than the capacity in the industry sector in the Netherlands (Blonk et al. 2010). Altogether with the building sector, the Netherlands has a 30 % share of cogeneration in the total electrical production of the country in the year 2014. This share is nearly twice as high as the share in Germany (AGEB 2016). For Germany, this could mean, that a growing, innovative SRG sector with CHP could provide flexibility for integrating the growing share of renewable energy.

The production of some species in the greenhouse can be energy intensive. For instance, fuel costs for heating and dehumidification in producing food in greenhouses in the German federal state of Baden-Württemberg can be up to 8.9 % of the operating income of a producer (ZBG 2015). Dehumidification is essential for plant health. In spring, summer and autumn periods thermal energy from the heating system is mainly used for dehumidify by ventilating and heating at the same time. Simulations show that up to 29 % of thermal energy in a greenhouse in Sweden is used for dehumidification (Maslak 2015). Estimations for greenhouses in the Netherlands assume that 20 % of the thermal energy is used for dehumidification (Stanghellini et al. 2016). Therefore, using waste heat in this sector can be an option.

Smart Grid integration

SRGs could deliver a demand side flexibility option with its energy demand for cooling, heating and artificial lighting to the smart grid. In a currently running German research project the flexibility option and the integration into the smart grid is analysed through a feasibility study (Schuch et al. 2016) (Kläring et al. 2016). A core component of the research is an energy simulation model for a greenhouse with time flexible artificial lighting and a heating system consisting of electrical heat pumps and a large-scale thermal energy storage with an integrated power to heat solution. The first published results show that the flexible artificial lighting isn't negatively affecting the photosynthesis of plants. For testing the whole system in a pilot project, the high investment costs for such technology is a barrier.

SRGs could enable urban food production in Germany based on renewable energy. This renewable energy could be produced in southern Europe, instead of transporting food with a fossil-powered road freight system from southern Europe to Germany. So SRGs can be "power-to-food" sector coupling option.

RESOURCE SYMBIOSIS (NO. 3)

It seems that there is a growing market for producing food in urban agriculture (Thomaier et al. 2015) and a commercial viability for producing food with rooftop greenhouses (Bambara and Athienitis 2015). An assessment of the growing market growth can be based on the growing number of companies, projects and project announcements[1] and also through market research reports which predict a strong growth (Markets and Markets 2016). Food in the form of vegetables is usually grown in hydroponic or aeroponics. Symbiotic production systems, like aquaponics which combines plant and fish production, enables further resource efficiency improvement (van WOENSEL et al. 2015) (Suhl et al. 2016).

Growing food for nearby consumers is shortening the supply chain. This minimizes costs and carbon emissions for food transport, can increase the food security and minimize food loses.

Another possible resource symbiosis is the production of bio-based manufacturing materials in the SRG. The literature review for this topic is out of scope of this paper.

SMART PLANT PRODUCTION THROUGH AUTOMATION AND DIGITALIZATION TECHNOLOGIES (NO. 4)

The energy and resource symbiosis between a SRG and a factory increases the complexity of the whole production and energy system. Enabling a high degree digital assistance or even autonomous production for the operators of SRGs offers the possibility to optimize the efficiency and flexibility of the whole production system delivering optimal process performance. Furthermore, it could enable to deploy SRGs in decentralized units for energy symbiosis usage without hiring a plant expert and skilled workers for every SRG unit. This could be important for some business cases, because in the cost structures for greenhouse food producers in the German federal state the salary expense can be up to 30 % of the operating income of a producer (ZBG 2015). Therefore, this section gives an introduction of the state of technology for closed loop control in plant production and proposes an interdisciplinary research to develop SRGs.

Smart mechanization, automation and robotic application for automated crop monitoring can support the SRG operator with digital assistance in the form of a decision support system for plant care and production. This enables resource and energy-use optimization in controlled environment agriculture (Story et. al. 2015). Technology innovation through automation and robotics can also be applied to the production process in SRGs. This means efficiently producing a large variety of individual species for example with the use of robot technology. The "FarmBot" is a illustrative example for fully automated horticulture based on innovative robot technology (Aronson 2013). The "FarmBot" is a CNC farming robot which enables automated seeding and plant care. This enables automated and mass customized plant production in lot size one. CAD files, hardware and software of the robot technology are open source. So this technology could be refined for SRGs and spin-off products could be developed. Adding evolutionary robotic automation for plant care represents a further step in the direction of a closed loop control self-organizing cybernetic system. One example for this approach the research field of bio-hybrid collaboration between robots and natural plants (Wahby et al. 2016). In addition, also plant picking and in the case of food also the packing and can be further automated.

The approaches described above and the technologies adopted are comparable to the Industry 4.0 approach and the development of cyberphysical systems (Bauernhansl et al. 2016). An interdisciplinary research approach, for example in the field of automatization and digitalization in manufacturing and the field of SRGs with robotic automation, could foster technical innovation between sectors and industries towards a scenario for the even closer interlocking of biology and technology.

Conclusion

The SRG concept has a high industrial and technological potential for urban growth regions in the 21th century. For exploring this potential the research project "Smart Factory – Smart Rooftop Greenhouses" carries out a feasibility study for a SRG demonstrator. Based on a positive feasibility study, the realization of a SRG demonstrator in a pilot project could be the basis for an evidence based assessment of the technical energy and resource efficiency potential as well as the calculation of the CO_2-mitigation potential of SRGs. The pilot project could also be a blueprint for the scalability of this approach. Furthermore, the pilot project could enable the participating companies to develop innovations for the sustainable manufacturing in smart cities.

There is one central weakness concerning the waste heat usage with SRGs. Using waste heat for greenhouses should only be considered when all other waste heat reduction and reintegration measures already are applied because waste heat can't be fully integrated in due to a certain seasonal variation of the heat demand. Due to heat demand for dehumidification in SRGs in the summer season, the seasonal variation of the heat demand is flattened.

1. Lufa Farms Inc., Canada (https://lufa.com/en/); Sky Vegetables Inc., United States (http://www.skyvegetables.com/); Gotham Greens Farms LLC, United States (http://gothamgreens.com/); UrbanFarmers AG, Switzerland (https://urbanfarmers.com/projects/the-hague/); Skygreens, Singapore (http://www.skygreens.com).

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