Urban Production: Smart Rooftop Greenhouses as a Technology for Industrial Energy Symbiosis

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ABSTRACT

One approach for advancing industrial 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 (SRGs). The main subject matter of SRGs is the combination of biomass production and waste heat usage from the factory as well as the smart grid integration of the collaborative production system.

As an SRG can be heated with low temperature waste heat, a big energy efficiency potential in German industry can be addressed. Furthermore, the SRG allows for space to be used more efficiently for supporting land-use reduction goals. With a highly automated and digitalized plant production technology in a controlled environment like an SRG, the production of high value biomass can be automated and optimized based on production output, energy efficiency and energy flexibility.

The aim of this publication is to present a concept for smart rooftop greenhouses. 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.

One new approach is the industrial energy symbiosis concept, which integrates the SRG into a micro-grid together with manufacturing processes. Another one is an interdisciplinary research approach combining industrial-manufacturing digitalization research with high-tech urban-farming research.

Introduction

Energy and resource efficiency does not have to stop at the factory gates. Industrial Ecology is a research field for holistically optimizing energy and 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 to integrate 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 ultra-efficient factories, can be attributed to research efforts in industrial ecology. The ultra-efficient factory is a new paradigm for industrial production. It aims to optimize the positive impacts of manufacturing on its surroundings instead of only minimizing negative effects (Lentes et al. 2017).

In this paper, the concept of SRGs (Reisinger 2017) is presented in a slightly extended version. 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. The "Smart Factory –

Smart Rooftop Greenhouses" research project's mission is to conduct a feasibility study for an SRG demonstrator.

Research results show that urban farming concepts like rooftop greenhouses can be an option for increasing energy efficiency in urban environments (Sanyé-Mengual 2015). Other forms of urban agriculture, like vertical farming which can be described as indoor farming in buildings (Despommier 2010), are using more energy for production at their current technological level, than comparable conventional production methods (Podmirseg 2015).

The Smart Rooftop Greenhouses Concept

SRGs presented in this paper are 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 into a digitalized and automated combination of industrial and biological production processes. This enables 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 figure. The literature review and further description of SRG elements are summed up in the sub chapters below.

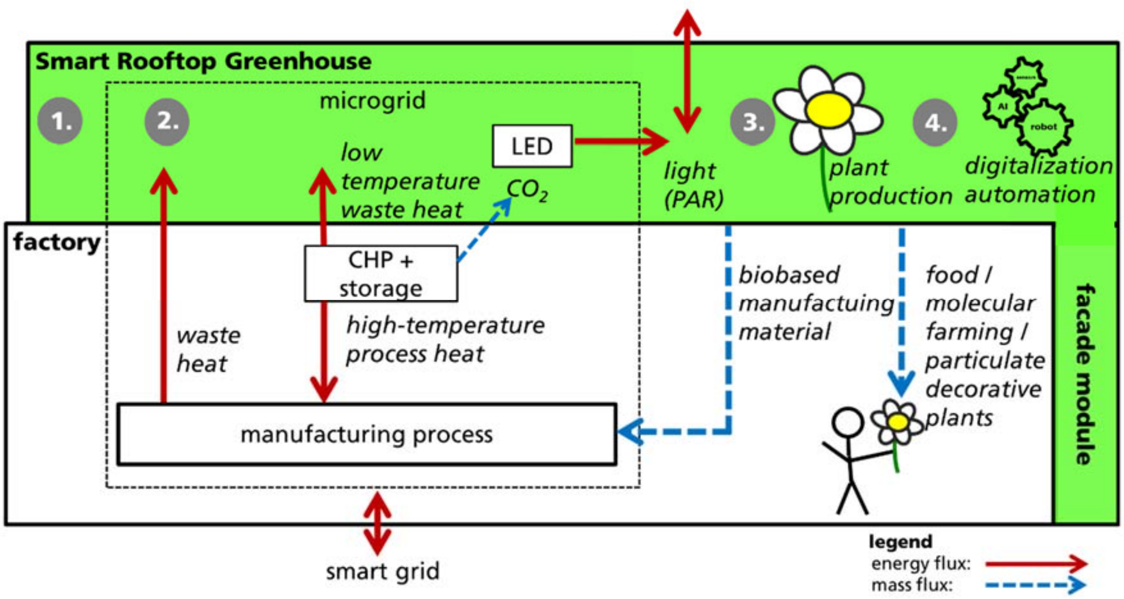

Figure 1: SRG concept [1.1] – technical conception of resource and energy symbiosis. The numbers enable the referencing of the following sub-chapters. (Remark: fluxes are explanatory and don't describe the complete system)

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 (CHP) units can be directly used for heating and CO2 fertilization of the SRG. This enables very efficient energy use 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 into the smart grid. The aim is to deliver energy flexibility to energy systems with a high share of variable renewable energy from wind and solar power. This flexibility may take the form of power-to-heat technology, flexible CHP capacity, time-flexible artificial lighting for plant production, or other methods. 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 that 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. Another market for highest-value plant-production can be the pharmaceutical industry, e.g. molecular farming. Decorative plants, e.g. for indoor offices, is another potential market.

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 will enable the use of biologically-based optimization approaches in both systems. Examples of this may include finding applications for sensing technologies and image processing software, originally developed for manufacturing systems in the field of optimal plant care. Plant production and picking is highly automated with robot technology while plant packaging and meal preprocessing is also realized through highly-automated technology.

Rooftop Greenhouse (No. 1)

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

Photovoltaic panels aside, industry and commercial facilities often have unused space potential on rooftops, facades and parking and logistics areas. Rooftop greenhouses can take advantage of this wasted roof space. This enables space efficiency by effectively doubling the usefulness of a given building footprint, limiting additional land use. This is important, as land consumption for settlement and infrastructure is growing. The land consumption objective of the Federal Government of Germany is to limit the land consumption within the country to 30 hectares per day. Currently, the land consumption rate is twice as big as the objective (Statistisches Bundesamt 2016) (Malburg-Graf et al. 2007).

However, there is the potential for competition between rooftop greenhouses and photovoltaics for roof space (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 wavelengths can be used for power generation with semi-transparent photovoltaics (Bambara and Athienitis 2015), e.g. luminescent organic photovoltaics technology (Corrado et al. 2016).

The SRG lowers the heat transmission through the building envelope from the factory, thereby lowering the site's heating and cooling demands. By combining the SRG with an evaporative cooler and integrating this system into 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 through the use of waste heat (Sauer et. al. 2016). In industry, not all waste heat can be reintegrated into the company's production processes. So an energy symbiosis, with an 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 CO2-mitigation targets in the Paris Agreement (UNFCCC 2015). There are other technical solutions for using waste heat – e.g. heat networks – but a comparison of SRGs to these technologies is outside the scope of this paper.

Using waste heat for heating greenhouses 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 (Pervilä 2012), has been a topic of research for decades.

For these kinds of projects, the general barriers for waste heat usage must be considered. The main barrier is project financing (Schnitzer 2012), as they are very capital intensive with much higher payback periods (Krause et al. 2015) than typical industry endeavors. Besides the capital intensity, 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 environments with controlled temperature, humidity, and PAR, the latter via artificial lighting. 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 on integrating the heat demand from greenhouses into heat networks. Specifically, for compensating decreasing heat demand due to deep energy efficiency retrofits in the network connected buildings. SRGs could also be an option for optimal energy usage in heat networks through the use of the heating networks' low temperature return flow.

The first large scale coupling of waste heat from energy production with greenhouses can be observed in the Netherlands, considered 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 a gas-engine CHP directly into the greenhouses, enables the use of low temperature waste heat in the flue gas for heating the greenhouse. The CO2 in the flue gas is used for fertilization in the greenhouses. The high temperature heat from the 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). 30% of 2014 electricity generation in the Netherlands came from cogeneration, nearly twice the cogeneration percentage in Germany for that year (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 plant 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 dehumidification by ventilating and heating at the same time. Simulations show that up to 29% of the thermal energy of greenhouses located in Sweden goes toward 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 their 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 are analyzed 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 large-scale thermal energy storage with an integrated power-to-heat solution. The first published results show that the flexible artificial lighting does not negatively affect the photosynthesis of plants. A barrier to testing the whole system in a pilot project is the high investment costs for such technology.

SRGs could enable urban food production in Germany based on renewable energy. Instead of transporting food with a fossil-powered road freight system from southern Europe to Germany, renewable energy produced in southern Europe could essentially be used by German SRG growers to the north. So SRGs can be a “power-to-food” sector coupling option.

Resource Symbiosis (No. 3)

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 market growth can be based on the growing number of companies, projects and project announcements[1] and also through market research reports which predict strong growth (Markets and Markets 2016). Food in the form of vegetables is usually grown in hydroponic or aeroponics. Symbiotic production systems, such as the combination of plant and fish production known as aquaponics, enable 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 food security and minimize food losses.

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

Smart Plant Production Through Automation and Digitalization Technologies (No. 4)

The energy and resource symbiosis between an SRG and a factory increases the complexity of the whole production and energy system. Enabling a high degree of 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 deployment of 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 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 a large variety of individual species can be efficiently produced with the use of robot technology. The “FarmBot” is an illustrative example for fully automated horticulture based on innovative robot technology (Aronson 2013). The “FarmBot” is a farming robot which enables automated seeding and plant care, developed with open-source CAD files, hardware and software. 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 is the research field of bio-hybrid collaboration between robots and natural plants (Wahby et al. 2016). In addition, plant picking and packing can be 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

[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 / see (http://www.skygreens.com)

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 21ths century. To explore this potential, the research project “Smart Factory – Smart Rooftop Greenhouses” carries out a feasibility study for an SRG demonstrator. Based on a positive result in that effort, the realization of an 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 CO2-mitigation potential of SRGs. These kinds of assessments could enable the monitoring of the low-carbon innovation potential of policy development for urban-production systems. 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 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 have already been applied, as waste heat can’t be fully integrated due to a 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.

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