NaWaM
Sustainable Water Management

ERWAS

Future-oriented Technologies and Concepts for an Energy-efficient and Resource-saving Water Management

Results

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Federal Ministry
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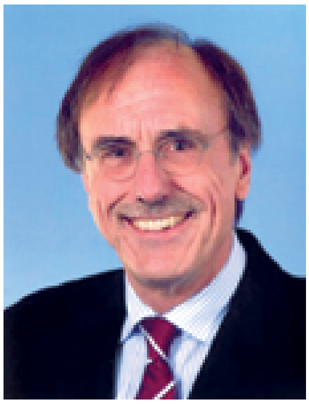
Future-oriented Technologies and Concepts for an Energy-efficient and Resource-saving Water Management

Results

Foreword



Sustainable water management plays an important role in our society. To secure a safe water supply of high quality for future generations, it constantly faces new challenges. Thus, the requirements for operators of water supply facilities and wastewater treatment plants rose during the last decades.

Despite the already high technological standards in Germany the energy saving potential in water management still amounts up to 25 % of electricity consumption. Therefore, an energy efficient water management not only plays a central role for the development of urban infrastructures but can also be a part of the energy turnaround. In addition, higher energy efficiency is linked to the reduction of climate affecting carbon dioxide. The wastewater treatment plants in Germany alone generate 3 million tonnes of CO_2 emissions per year.

In order to use this potential, new research ideas and approaches are necessary. Therefore, the Federal Ministry of Education and Research initiated the funding measure "Future-oriented Technologies and Concepts for an Energy-efficient and Resource-saving Water Management" in 2012 and funded the programme with 28 million €.

Within the research projects, researchers analysed the interface between water management plants and surrounding energy grids. The results form the basis for possible components of a future energy efficient, decentralised infrastructure which are based on renewable energies.

All ERWAS joint research projects included not only scientific institutions but also partners from economy and water management practice. Technologies, pilot plants and prototypes were tested and now they have to prove their practicability. Thus, application perspectives were developed with partners from practice right from the beginning.

ERWAS showed that the water-energy-nexus gives the crucial incentive for new energy and resource efficient solutions. In the long run, everybody benefits from these innovations, since cost saving in water management affects users as well. The key results of the joint research projects are presented in this brochure.

Karl-Eugen Huthmacher

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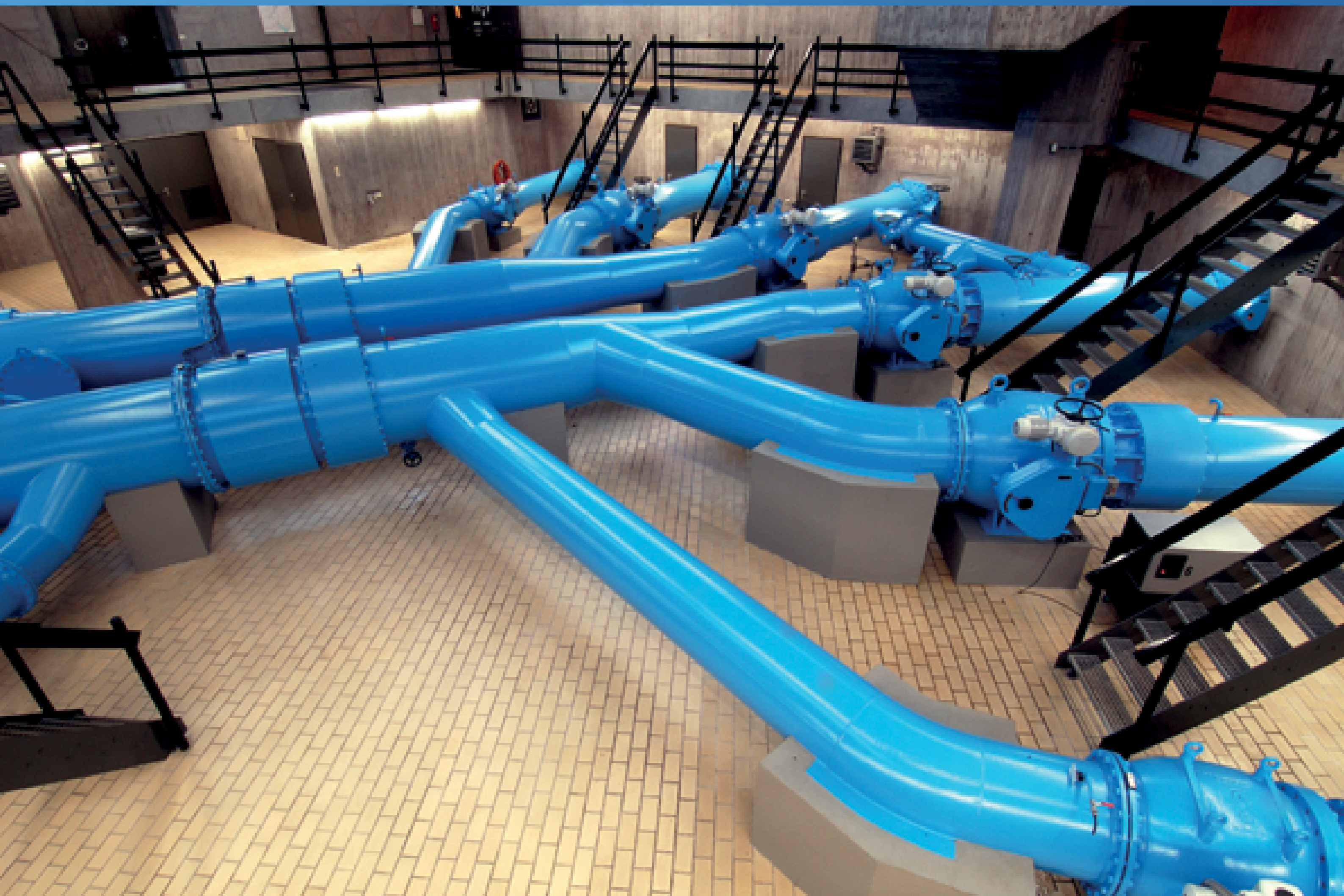

The BMBF funding measure ERWAS

The BMBF funding measure ERWAS

Introduction

Results

Without energy, neither wastewater treatment plants nor water supply systems can be operated. The existing German facilities for public water supply and wastewater treatment alone, consume 6.6 TWh of electrical energy per year, which is equivalent to the annual electricity requirement of about 1.6 million four-person households. Beyond higher energy efficiency, resource-efficient energy generation is possible at most sites. For example, innovative approaches in wastewater treatment could gain energetic autonomy or even "energy positive" plant situations.

Although, this framework and chances are known since the 1990s crucial success in resource and energy efficiency didn't appear, even if single plants could achieve substantial progress. This was not due to a lack of will of the stakeholders but due to the lack of innovative approaches. So, new possibilities and potentials had to be developed. At this point the ERWAS funding measure with its 12 BMBF funded joint research projects and about 80 partners begins (see fig. 2).

After the completion of work of most of the projects, this brochure presents the comprehensive results in brief. Further insights can be gained from the research reports of the joint research projects.

Fig. 1: Wastewater treatment plant Goslar/Germany (Sabine Thaler, DWA)

The joint research projects

A major focus of the funded projects was the development of new concepts for the interaction between the drinking water, wastewater and energy sectors. Examples are provided by the use of the load management potential and the energy storage capabilities of the water management sector for the future energy systems. Here, among other things, research is to be carried out into the extent to which water management facilities will be able to play a balancing role as an energy source or sink given by the more fluctuating electricity supply from renewable sources (wind and solar) in future.

Furthermore, innovative methods of energy production and energy conversion in water management facilities have been developed, along with the optimised power generation in microbial fuel cells or the conversion into methanol. New ways to improve exploitation of the energy potentials in sewage sludge with simultaneous utilisation of the resources contained in wastewater, such as phosphorus, were also a priority.

Concerning the water supply plants several joint research projects focused on the use of the energy potential with a priority on process optimisation. Another research topic was the energy optimisation of future plants concerning the elimination of trace substances.

Drinking water supply	**ENERWA** **EnWasser** **EWave** **EWID** **H_2Opt**
Microbial fuel cells	**BioBZ** **BioMethanol** **KEStro**
Wastewater treatment	**arrivee** **E-Klär** **ESiTI** **KRN-Mephrec**

Fig. 2: Projects of ERWAS funding measure

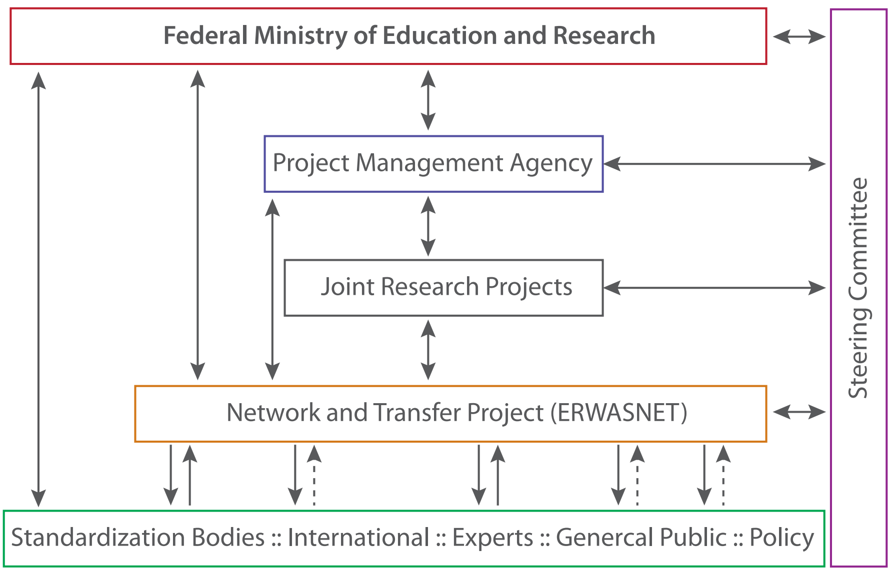

Fig. 3: Structure of the funding measure

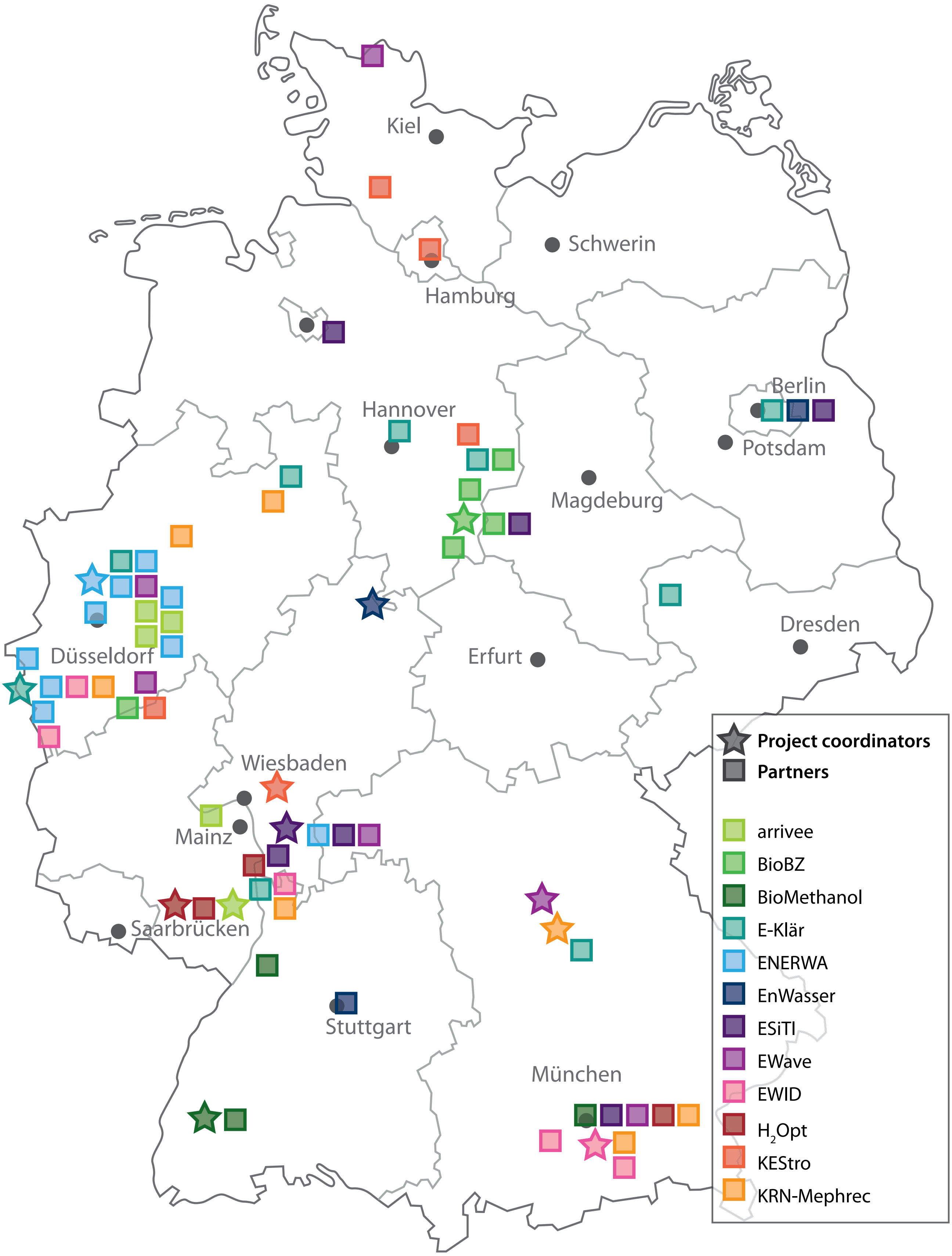

Fig. 4: BMBF funding measure ERWAS – Location of participating institutions
Map of Germany

The steering committee

The work of the joint research projects formed the centre of the funding measure. These projects were also supported by a steering committee as an accompanying body. As with all funding measures within the framework of the BMBF funding priority NaWaM (sustainable water management), the steering committee worked at the interface between research and practice, to ensure that the research will deliver practice-oriented findings that are capable of implementation. Members from business, the authorities and other institutions, who are involved in the subject of "water and energy" in different ways as part of their daily work, were appointed to the steering committee. The project coordinators of all twelve joint research projects were also members of the steering committee, so that a direct exchange of knowledge and information is guaranteed.

Fig. 5: Members of the steering committee

The networking and transfer project

The funding measure ERWAS is accompanied by an independent networking and transfer project (ERWASNET) that carries out organisational and substantive tasks. It supports the joint research projects performing their work. This networking and transfer project ERWASNET is carried out by a consortium consisting of the German Association for Water, Wastewater and Waste (DWA) and the engineering company of water, wastewater and energy TUTTAHS & MEYER (Ingenieurgesellschaft für Wasser-, Abwasser- und Energiewirtschaft mbH).

Fig. 6: Presentation of the interim results at the ERWAS-conference February 2016

The tasks of ERWASNET are the preparation, performance and monitoring of meetings, workshops, panels and status seminars on comprehensive questions; the development and provision of information materials on the funding measure (press and promotional materials, website, etc.); ensuring coordination with the standard setting associations of the water management sector to enable the utilisation of the research findings in the technical rules and standards as well as networking with relevant national and international activities.

Internationally, four major events of the water-energy-nexus were visited (Washington, D.C., Stockholm, Malmö and Exeter). In summary it can be stated, that the joint research projects are at the top of the technological development at international scale.

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The BMBF funding measure ERWAS

ERWAS cross cutting issues (QT)

As already known at the beginning of the ERWAS funding measure it turns out that there are interfaces and aspects which would be interesting across projects, for instance procedures, methods or subject-specific issues. In order to unite this work and to actively use the possible synergies, the steering committee defined four cross-cutting issues (Querschnittsthemen QT), which were elaborated in integrated working groups. These four groups were founded:

- QT Biofuel cell (BZ)
- QT Sewage sludge
- QT Energy storage and energy grids (ESpEN)
- QT Modelling and simulation

The cross-cutting issues were supported with high commitment by the project partners and a lot of relevant results for research and practical use were developed. In the following, the essential results are presented briefly.

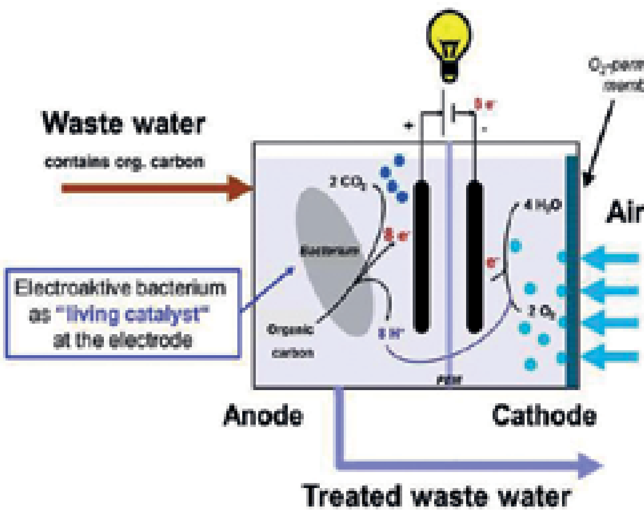


Fig. 1: Operation principle of a microbial fuel cell for simultaneous generation of electricity and waste water treatment (Source: IMTEK).

QT Biofuel cell (BZ)

The 3 joint research projects BioBZ, BioMethanol und KEStro worked on different aspects of the development of microbial fuel cells (fig. 1) resp. electrolysers and collaborated within the cross-cutting issue with high effort. The participants valued the exchange and discussions for their own joint research projects. Synergies were found and common challenges identified within the QT and with external stakeholder. These results were included in the work of the projects and were the base for lectures and publications.

Under this premise a successful workshop headed by BioBZ on the subject "Microbial fuel cells and electrolytic cells" was conducted with participants from industry, practice and research. A report about the activities of the QT was published in the KA (DWA journal on wastewater and waste) within the special topic issue of "Research Energy Water". It is also planned to publish the results in the series "DWA topics" as "Microbial fuel and electrolytic cells in wastewater treatment".

Due to the ERWAS bio fuel cell projects and the joint activities within the QT BZ, the operation of microbial fuel cells and electrolysers in wastewater treatment plants has been explored in a stage that pilot runs in larger scale are now possible. If the demonstrated potential of this technology is approved in larger scale, this could introduce a technological turn in wastewater treatment.

QT Energy storage and energy grids (ESpEN)

At the determination of the cross-cutting issues it became clear that the significance of the role of the water sector within the "power market for the energy turnaround" is a comprehensive topic of many ERWAS joint research projects. So, 9 of the 12 projects joint the QT Energy storage and energy grids (ESpEN) in which initially the topic balancing energy potential of water treatment and water supply plants should be dealt with in particular. But quickly it became clear that this topic could not be reduced to balancing energy. The aim "Investigation of the balancing energy potential" was extended to "Investigation of the flexibility potential".

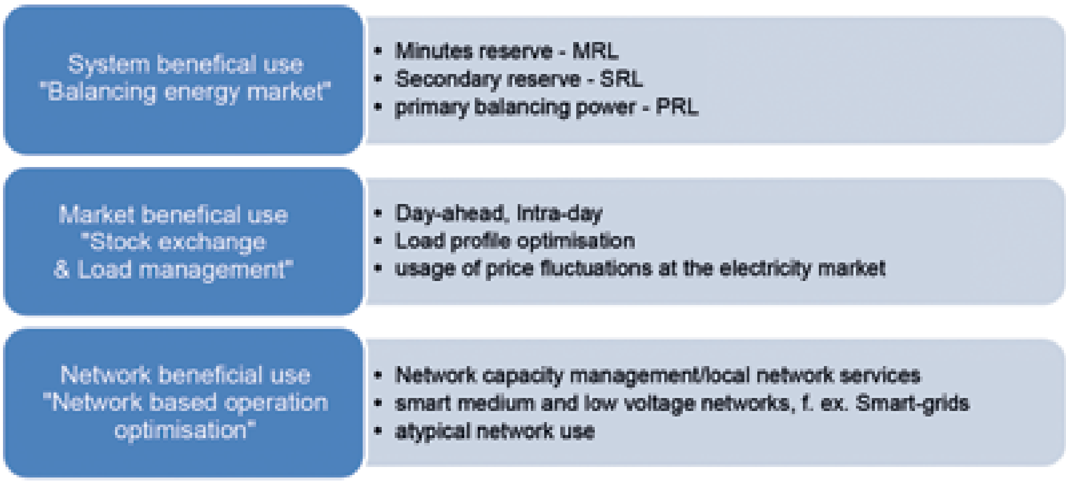


Fig. 2: Possible application for flexibility, modified in accordance to (Gretzschel et al., 2015)

The detailed knowledge about individual components and systems, load profiles, peak demand, characteristic curves and efficiencies forms the basis for the optimised usage of „flexibility components“.

Based on this information operators can realise f. ex. revenues for switching off and on of loads, optimising load distribution or reducing the network charges. The more detailed the operating data is gathered and the more quickly and reliable the provision of flexibility is possible; the higher are the possibilities for revenue.

On this basis the flexibility options within different markets could be recognised and system beneficially applied (see fig. 2).

The network beneficial use takes place at different levels of the distribution networks and is aiming at obtaining the voltage. The market serving usage contains the different products of the power exchange and doesn't involve system and network beneficial functions in the first place.

One of the possibilities is to bring flexibility of small and medium sized plants to market the so called "virtual power plant". It summarises the flexible services of different plants and providers and offers these services as a bundle to the energy markets (see fig. 3). With the pooling with other water management plants the actual performance goal of 5 MW within the network is easily achievable and could be marketed without additional effort for the plant operator.

To what extent water managements plants could be used for the application fields presented by the joint research projects depends on a high degree on the legal framework and its future organisation.

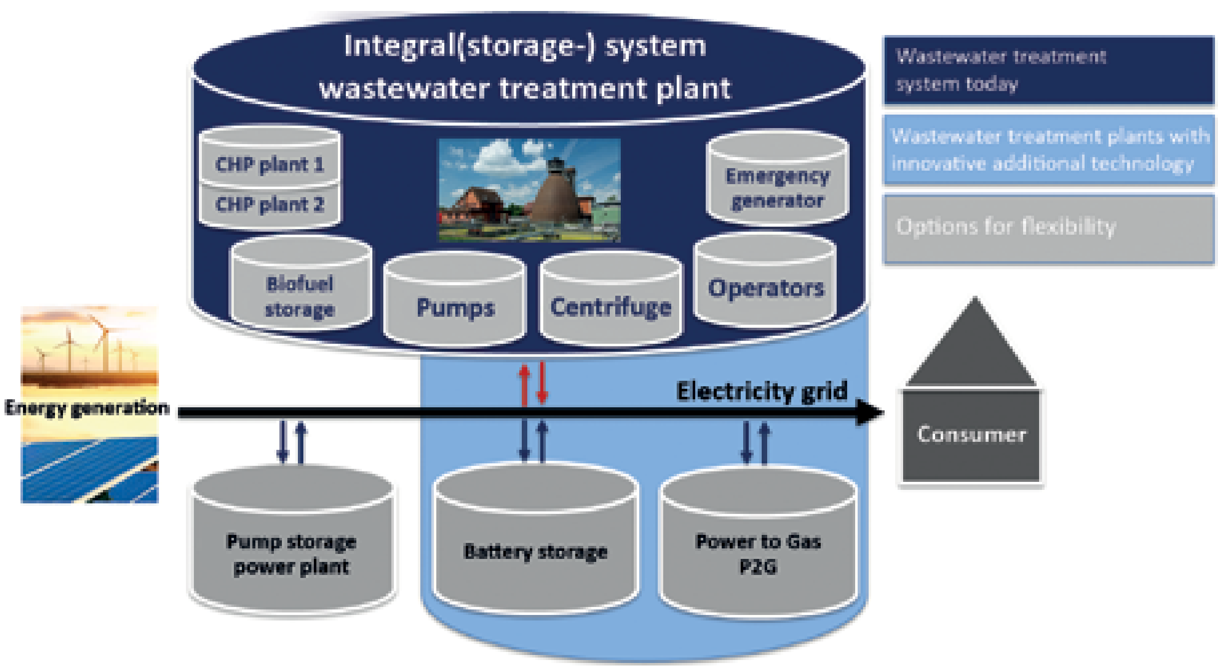


Fig. 3: Wastewater management systems as flexibility components for energy management

QT Sewage sludge

The ERWAS interdisciplinary topic "Utilisation of sewage sludge as energy resource: Sewage sludge and co-substrates, biogas, sludge recycling" (ERWAS-QT- Sewage sludge) serves as network for the joint research projects in the field of "Energy and sewage sludge". In particular, these were participants of the projects arrive, E-Klär and ESiTI.

According to the new DWA (German association for water, waste water and waste) standard A 131 „Design of single stage activated sludge plants", the design of the biological treatment step will be based on the COD. The participants of this QT discussed the adaptation of the design parameters regarding the sewage sludge treatment. They thought it absolutely crucial to adapt the sewage sludge design in order to facilitate a solid energy balance of the whole wastewater treatment plant.

In practice, different methods are currently applied for analysing the COD. It has to be clarified whether these methods provide equivalent results concerning the adaption and development of design parameters and the application under benchmark processes.

The participants of this QT thus conducted a comparative analysis with respect to the COD. It was aimed to compare the various methods of analysis (including the preparation and treatment of samples), in order to draw conclusions about plausibility and reproducibility of the measurement results regarding the sewage sludge samples.

The results of these comparative analyses could show essentially that all applied analysis procedures are fundamentally very well suited as COD measurement. These analyses show differently-sized deviations depending on the sample type (Homogeneity of solid fraction, fat content) (see fig. 4). Procedures were beneficial, when the original sample could be analysed without further sample preparation (drying and grinding) and with low or no dilution.

Based on the results and on the increasing relevance of the parameter COD the participants of the QT recommend to standardise future sewage sludge analyses. The results of these comparative COD analyses were published in the DWA journal KA in April 2016 and as a poster at the annual meeting of the Water Chemistry Society "Water 2016". Furthermore the results will be integrated into the revision of DIN 38 414-09.

A comparative measurement of laboratory fermentation is currently carried out. The procedure is analogous to the COD comparative measurement. In this context it is intended to analyse the influence of the test setup and realisation as well as the influence of the activated sludge on the result.

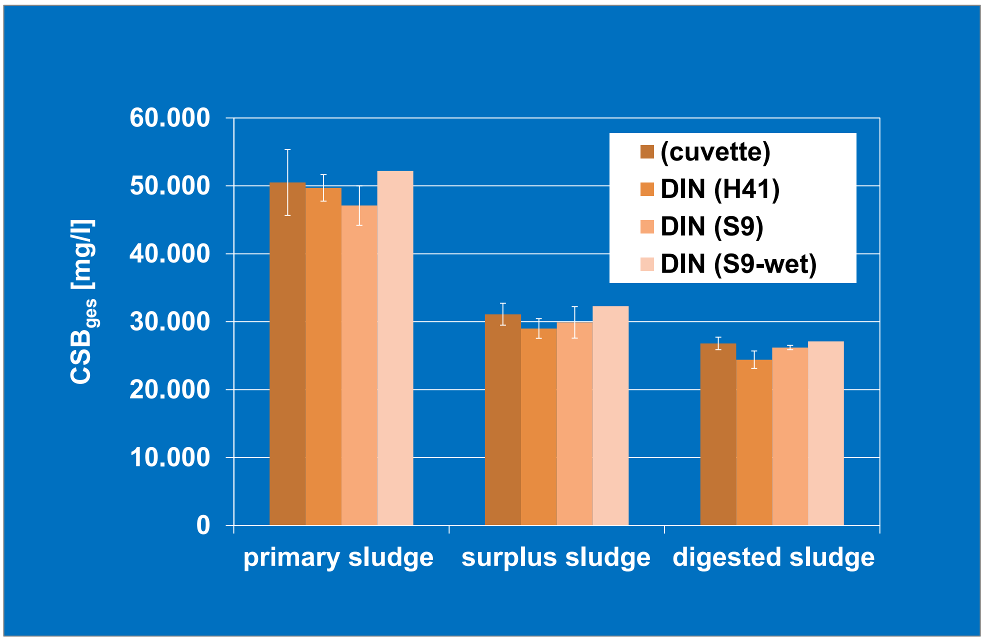


Fig. 4: Results of the COD comparative measurements

QT Modelling and Simulation

Within the QT Modelling and Simulation 30 reseracher of the joint reserach projects arrivee, E-Klär, ENERWA, EnWasser, EWave, EWID, H2Opt and KRN-Mephrec exchanged their views. At regular meetings project achievements and modelling approaches and strategies were presented and discussed. In addition to problems which occurred during the modelling process, further common issues were discussed.

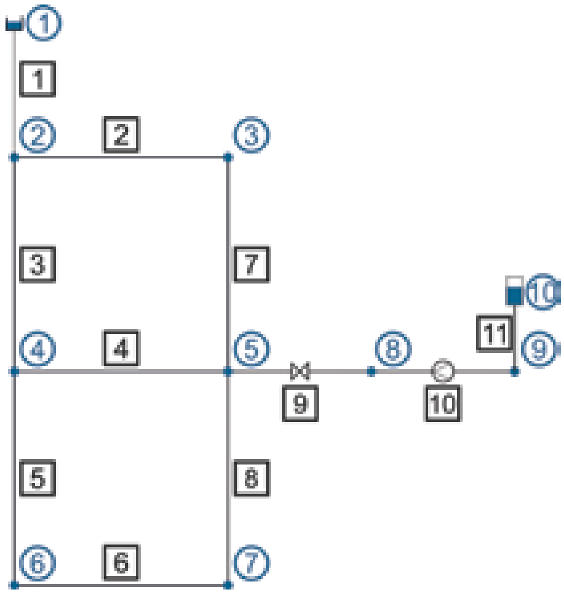


Fig. 5: Pipeline network of the 2. benchmark

This included methods of pipeline calculation and of the prognosis of drinking water use, the robustness of simulations, the development of efficient optimisation processes and the validation of simulations.

To compare the developed pipeline calculator of the different joint research projects, two benchmark tests were performed. With these tests, the simulation results of the commercial pipeline calculator AFT Fathom 7.0 and the open-source software EPANET 2.0 were consulted as reference. Figure 5 shows the pipeline network of the second benchmark.

The network contains 8 nodes which are linked via 9 pipes, one outlet and another pump. At the top end is a reservoir and at the right end a tank with which water is fed to the network. The geodesic altitude of the network nodes differs from each other as well as the water use within the nodes. The pipe diameter varies between 300 and 600 mm whereas the length of the pipe is 1000 m. In comparison with the first benchmark, for the second benchmark a "virtual" water plant with valve, pump and tank was added. The water plant is connected at node 5 and can be regulated with the valve between node 5 and

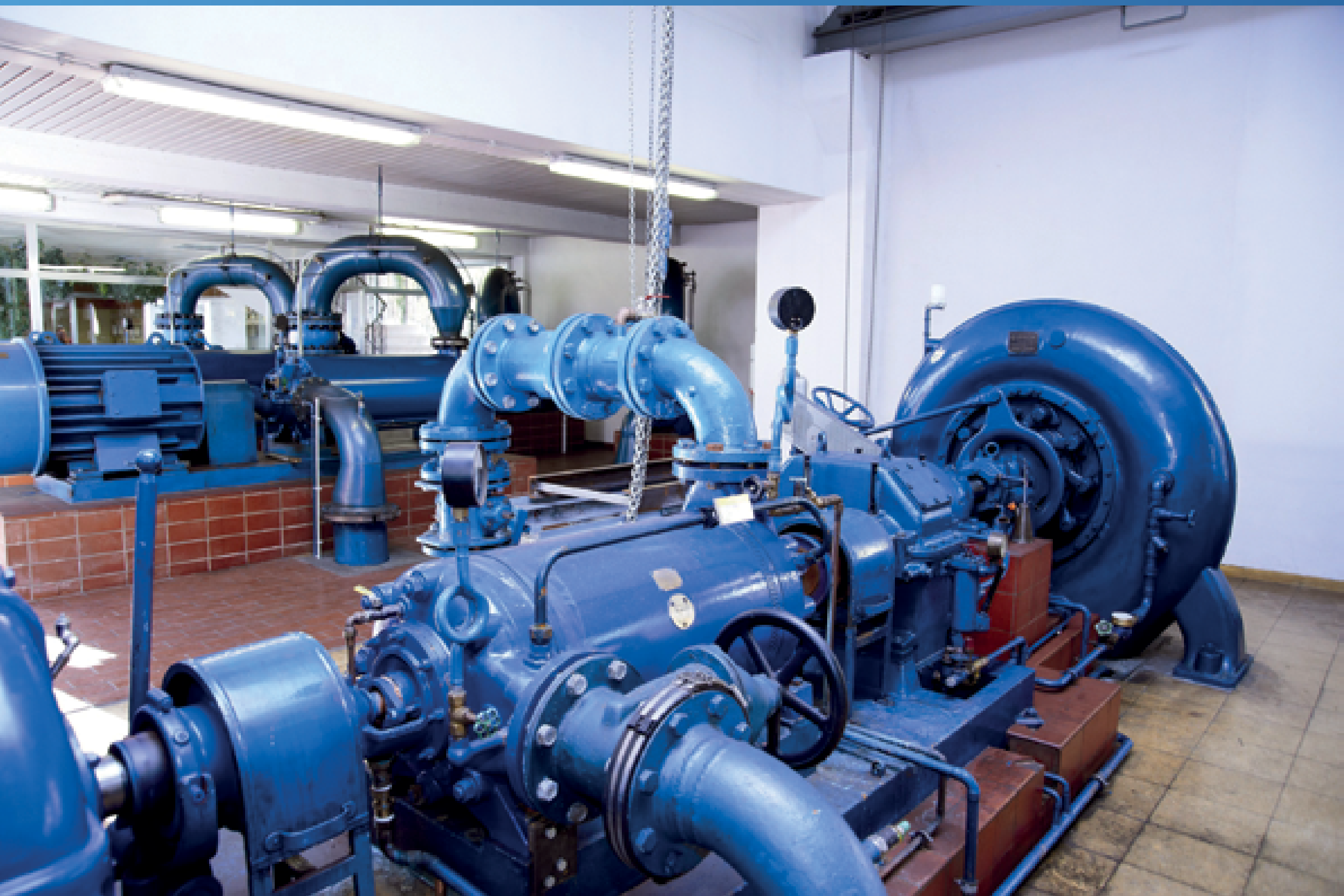
Pipe	Flow rate [m³/h]				
	AFT Fathom 7.0	ANACONDA (EWave)	EPANET 2.0	RZVN Wehr GmbH (ENERWA)	TWaveSim (EWave)
1	1120,00	1120,00	1120,00	1120,00	1120,00
2	383,46	383,26	383,41	383,30	383,26
3	636,54	636,74	636,59	636,70	636,74
4	153,48	153,36	153,47	153,35	153,36
5	363,06	363,38	363,12	363,35	363,38
6	33,06	33,38	33,12	33,35	33,38
7	283,46	283,26	283,41	283,30	283,26
8	166,94	166,62	166,88	166,65	166,62

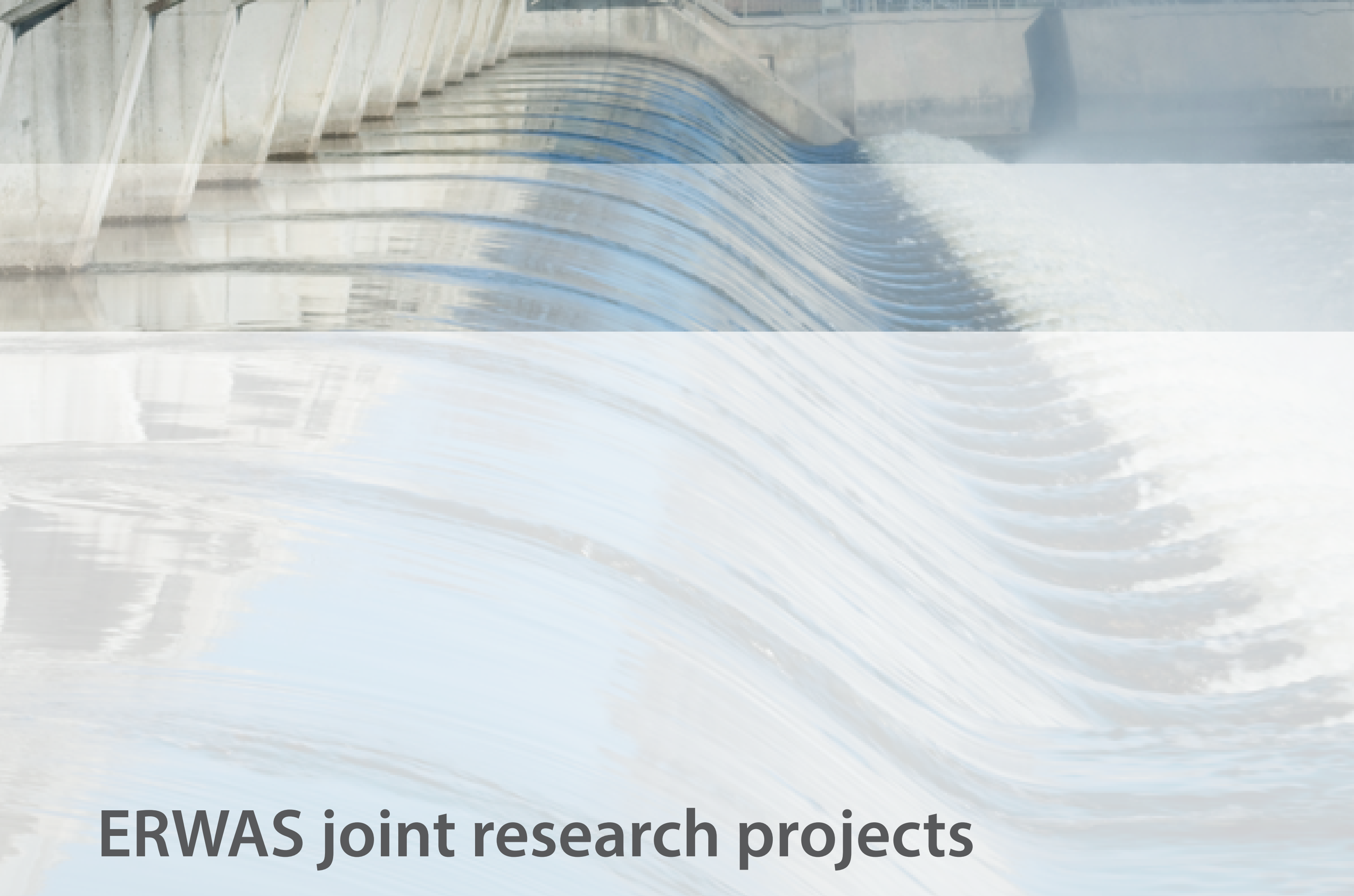
Tab. 1: Flow rate within the network with shut valve

Nodes	Pressure distribution [m]				
	AFT Fathom 7.0	ANACONDA (EWave)	EPANET 2.0	RZVN Wehr GmbH (ENERWA)	TWaveSim (EWave)
1	210,00	210,00	210,00	210,00	210,00
2	208,23	208,23	208,25	208,24	208,23
3	206,52	206,47	206,52	206,50	206,47
4	203,62	203,52	203,60	203,57	203,52
5	202,36	202,22	202,32	202,28	202,22
6	202,09	201,94	202,05	202,00	201,94
7	202,03	201,86	201,97	201,93	201,86

Tab. 2: Pressure distribution within the network with shut valve

8. At the second Benchmark the value of the pressure loss ζ of the valve was varied and so different reduction grades were adjusted. So the pipe network could be simulated and analysed at different outputs of the pump and so at different operation states at the water plant. Table 1 and 2 show the calculated flow rates (flow rate and pressure distribution) in the case of a closed valve. The comparison between the different pipeline calculation shows that the simulation results – both of the flow rate at the respective pipes of the network and the overall pressure head at the nodes – differ only by a maximum of 0,2 %. By the comparison of the simulations of further operating states the pipeline calculation could be verified among each other.





ERWAS joint research projects

BioBZ

The bio-electrochemical fuel cell as a component of an energy-producing sewage treatment plant

Background

At the moment, the energy in municipal sewage is transformed into electrical energy by sewage sludge digestion with subsequent utilisation of the digester gas via combined heat and power. Thereby, about 8-12 % of the chemically bound energy within the raw wastewater is transformed to electricity, which covers 50 to 80 % of the own energy demand of the wastewater treatment plant. A new approach to increase the own share is the immediate transformation of the chemically bound energy of dissolved organic wastewater ingredients into electricity.

This approach is pursued within the joint research project "The bio-electrochemical fuel cell as a component of an energy-producing sewage treatment plant". Bio-electrochemical fuel cells should be developed from the laboratory scale to the half-technical scale and be further analysed and rated in regard to practical use. Thereby, the contribution of the system to the improvement of energy and resource efficiency of wastewater treatment plants as well as the technical prospect and economic application are of huge interest. Accompanying analyses of the micro-pollutant elimination and the characterisation of "electricity-producing" biofilms provide further insights to judge the additional value of such systems.

Results

The results involve different development and analysis foci and are summarised in the following section.

(1) Material development: For the anaerobic operated cells, electrode slabs on the basis of graphite-polymer-mixtures were developed. For the aerobic operated cells graphite laminated stainless steel fabric electrodes were developed. To minimise the deposit effect at the electrode and to increase the long-term power, a catalyst-graphite mixture on the basis of molybdenum disulfide and manganese dioxide were developed.

(2) Scale-up: The material and power characteristics of the cell were optimised at the scale 13x15 cm^2 and verified at the next slab scale at 15x70 cm^2. The sectoral power concentration were similar in the range between 150 and 220 mW/m^2 so the semi-technical pilot plant was developed with a slab scale of 45x70 cm^2 and a total surface of 30 m^2. Information from biofilm characterisation support the design in respect of the overflow speed.

(3) Reactor concept / Integration at wastewater treatment plants: A dive module concept was developed which can be integrated easily in the aeration tank. A part winning method for the COD was developed after the primary clarifier to secure sufficient COD for further nitrogen elimination if necessary. Furthermore, the use within the sludge of the digestion is possible with a similar high special power.

(4) Control technology and harvest/storage of electricity: To analyse the operational characteristics of the cells, constant power sources were developed. Thereby it was shown that every cell – even if they are identically constructed and operated – needs an own cell voltage for their power optimum. The development refers to the harvest and storage of the micro-organic produced electricity. Electronical circuits for voltage conversion and electricity storage were designed as well as direct current voltage conversion to generate commercially useable voltage from 2.5 V and to store the electricity (level of efficiency 70 %).

(5) Long-term performance: At the moment, secured results of the long-term performance are only available for the smaller cells. Some cells could be operated for 1.5 years almost maintenance-free at 50 to 150 mW/m^2. Higher performance led to scaling and fouling effects by which performance losses occurred. This loss was minimised resp. avoided during the time of the project by the above mentioned development of a catalyst (actual period of evaluation: 5 month).

(6) Micro-pollutant elimination: The laboratory analysis of model substances from different substance classes showed a substance specific capability to eliminate at the bio-electrochemical fuel cell starting at easy eliminable (for example Erythromycin, Diazepam, caffeine) to sparsely eliminable (Enrofloxacin, Diclofenac, Carbamazepin). In addition, the capability to eliminate depends on the dwelling time of the wastewater within the bio-electrochemical fuel cell.

(7) Hydrogen production: Different catalyst materials were tested in respect to their performance regarding hydrogen production and resource efficiency. The 1,4401-Steel alloy (V4A-Steel) was the best combination of good catalytic ac-

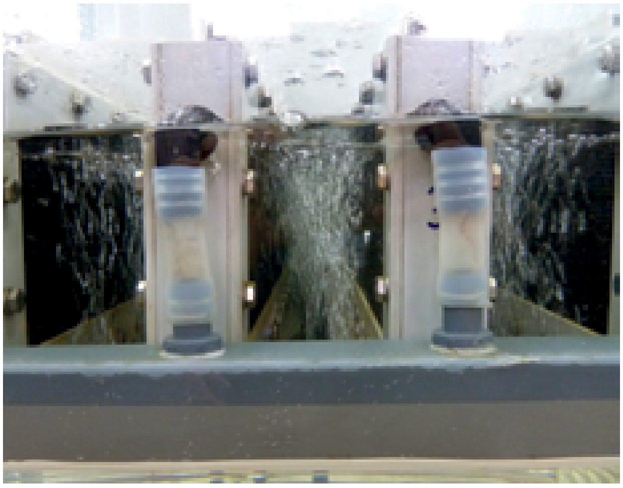


Fig.1. Pilot plant (Sabine Thaler, DWA)

tivities and low corrosion rate. At the same time it is the best choice economically for the cathodic hydrogen production in technical scale.

(8) Assessment of the energy and resource efficiency: With the equilibration of CO_2 equivalents for material consumption and energy generation of a bio-electrochemical fuel cell an integrated assessment was conducted. It was shown that the analysed CO_2 balance will be positive after only 2 to 3 years (CO_2 reservoir) as the decrease of the CO_2 emissions exceed the CO_2 consumption by material consumption.

The efficiency of the electricity production (ratio electrical energy to chemically bound energy) with bio-electrochemical fuel cell is about 12-17 % in respect to the degraded COD. The possible contribution of a wastewater treatment plant depends on the dimension. At larger plants from 10,000 population equivalents (EW "Einwohnerwert") the COD removal is limited to avoid impairing the denitrification. The contribution to the energy balance of COD reduction is about 18g per EW, about. 3.5 kWh/(EW.a). Wastewater treatment plants with larger C/N-ratios within the raw wastewater and at wastewater treatment plants with lesser requirements to the nitrogen elimination, energy generation of about 8 kWh/(EW.a) is possible at a COD reduction of 40 g/EW (34 % of the COD within the raw wastewater).

These numbers illustrate that the bio-electrochemical fuel cell can enable energy generating wastewater treatment plants at the basis of COD in raw wastewater at a larger COD removal (for example in combination with deammonification). Particularly profitable is the combination with digestion as the primary sludge and the (remaining) surplus sludge still have to be stabilised.

Conclusion

At this joint research project a semi technical bio-electrical wastewater treatment plant was developed and attempted successfully – first-time in Germany. The scale-up factor was 1.500. The essential project progress was:

- Development of new production and alloy processes for composite-electrodes and membrane electrode-units for batch production
- Development of new electronic products for the cell control and the voltage conversion and electricity storage
- Development of new efficient and long-term stable catalyst mixtures
- Development of a low energy dive module concept
- Application of optimisation tools like biofilm characterisation methods, biofilm conditioning methods and flow simulation

Potential and demand for improvement is a higher profitability in material consumption and production costs. But this was expected as the aim of the joint research project was the demonstration of feasibility and implementation. An added value is the trace substance elimination which cannot be valued monetarily at this moment.

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Duration: 05/2014 – 10/2017
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BioMethanol

Sustainable synthesis of the energy-carrier methanol from waste water

Background

As an alternative technology for a more energy-efficient wastewater treatment microbial fuel cells are currently being developed. In microbial fuel cells, so-called exo-electrogenic bacteria use the anode of a fuel cell as terminal electron acceptor instead of oxygen simultaneously producing CO_2 and protons from organic carbon (fig.1). At the cathode, oxygen reduction completes the electron cycle. This way, electricity can be directly generated from the energy-rich organic carbon fraction of the wastewater while at the same time the energy-intensive aeration can be circumvented. If the cathode is placed in an oxygen-free environment protons instead of oxygen are reduced at the cathode and hydrogen gas is generated. Thereto an additional small voltage has to be applied between the anode and cathode of the fuel cell. This process is called microbial electrolysis. Compared to conventional electrolysis this process requires less electricity, since part of the required electrical energy is supplied from the bacterial degradation of the wastewater at the anode.

Scope of the interdisciplinary and collaborative project BioMethanol is the production of carbon dioxide (CO_2) and hydrogen (H_2) from municipal or industrial wastewater in a microbial electrolysis cell, and their further conversion into methanol by a downstream heterogeneous catalysis process. Overall aim of the project is the characterization of a complete laboratory scale system for the production of methanol from wastewater and the ecological and economic evaluation of the overall concept „sustainable methanol from wastewater“. For this purpose, an optimized microbial electrolysis cell for the production of H_2 and CO_2 as well as improved catalysts for the methanol synthesis reaction will be developed.

Results

Regarding the development of the microbial electrolysis cell, a carbon-supported MoS_2 catalyst was developed as a cost-efficient alternative to platinum. Compared to the established platinum electrodes the new material exhibits a significantly improved performance in real industrial wastewater, with by approx. 0.4 V reduced overpotentials. Due to its markedly lower price (at less than 5 € m^{-2} the electrode's material costs are approx. two orders of magnitude lower compared to a platinum electrode) and improved performance this newly developed material is particularly promising for practical application.

At the same time, the performance of the microbial anode has been improved by inoculation with defined microorganisms. The successful procedure involves a mixed microbial consortium and its slow adaption to

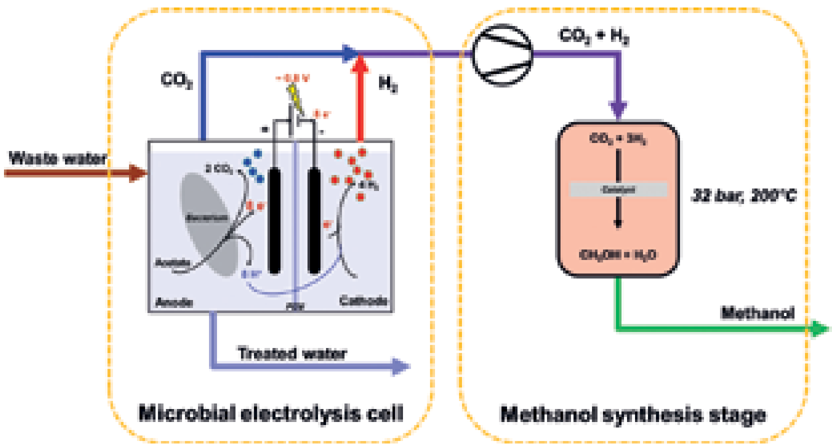

Fig. 1: Schematic representation of renewable methanol production from industrial or municipal wastewater. A) Microbial electrolysis cell; B) Methanol synthesis (Source: IMTEK)

Fig. 2: Laboratory setup for the parallel operation of up-scaled microbial electrolysis cells (36 cm^2 geometric electrode area) with industrial wastewater. (Source: IMTEK)

operation with the real industrial wastewater. The microbial consortium consists of the electroactive bacterium Geobacter sulfurreducens and further species, isolated from the wastewater of the cellulose acetate production plant. In laboratory experiments we could show that the new procedure enables an 80 times increased current density of up to 1.2 A m^{-2}. At present, this inoculation strategy is being transferred to complete up-scaled microbial electrolysis cells (fig. 2). In first experiments, already current densities of more than 4 A m^{-2} have been reached

Regarding improved catalysts for methanol production, a promising new synthesis route for a fluorinated catalyst based on a precursor with high carbonate fraction has been developed. Its main advantage over the established synthesis route is the conservation of the catalyst's carbonate structure. At present, this catalyst shows a selectivity of 80% for methanol at 200°C and 40 bar, which corresponds to an increase by 10 percent points compared to the benchmark. In addition, the in-situ downstream synthesis of dimethyl ether (DME) from methanol has been successfully established by using two different catalyst materials in the same reactor. Compared to the benchmark, this approach leads at present to a by approx. 20 % increased CO_2 turnover. At a roughly three times higher price, DME is also a more attractive product than methanol, which can significantly improve the economic feasibility of the process.

To enable an evaluation of the economic and ecologic potential of the technology a model of the overall system was established. It comprises investment cost of relevant system components and considers different future scenarios for the market price of energy (electricity) and methanol. Preliminary calculations already revealed that the use of CO_2 from external sources negatively affects the economic feasibility and ecologic impact of the process. Furthermore, the achievable current density of the microbial electrolysis cell and the associated area of membranes and electrodes is one of the main cost factors.

Conclusion

In the course of the collaborative project new materials and processes were developed that enable a significant improvement of the overall concept „sustainable methanol from wastewater" under conditions relevant for practical application. Regarding the microbial electrolysis cell operating on industrial wastewater, these are cost-efficient and highly active hydrogen evolution catalysts as well as a new inoculation procedure to increase the so far limiting anode current density. With respect to methanol synthesis, the new catalysts not only enable increase turnover and productivity, but with dimethyl ether (DME) an economically advantageous downstream product can be obtained.

From the very beginning of the project the ecological and economic evaluation of the overall concept was very helpful. This way, already at an early stage of process development factors that limit overall performance (e.g. the achievable current density at the microbial anode) could be identified and specifically optimized.

At the end of the project the two sub-processes „microbial electrolysis" und „methanol/DME synthesis" will be combined in a laboratory scale system for the sustainable use of organic carbon from (industrial) wastewater. Its detailed characterization will provide data for the ecological and economic evaluation of the overall concept and can serve as a basis for the realization of a pilot plant in a follow-up project.

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KEStro

Wastewater treatment plants as energy stabilizer for power grids

Background

The amount of energy provided by renewable sources, e. g. wind and solar power, is constantly increasing. Availability of renewable energy is subject to fluctuations. To balance this fluctuations energy storage systems are required, e. g. pumped-storage reservoirs.

Wastewater treatment plants can also be used as energy buffering systems. In this project an energy buffering system operating in wastewater treatment plants shall be demonstrated. This novel system consists of a microbial fuel cell as energy source and an electrolysis of micropollutants as energy drain. These components are switched on and off depending on the energy demand. Both systems do not only stabilize power grids but do also contribute to wastewater purification. The development and the testing of these two components and the complete system are the objective of this joint project.

Results

In a microbial fuel cell organic wastewater ingredients are decomposed at a biofilm-covered electrode (anode) what leads to the production of electricity. On the other electrode, a gas diffusion electrode (cathode), atmospheric oxygen is reduced to water (hydroxide ions).

The microbial fuel cell was tested under laboratory conditions with synthetic (substrates: acetate and humic matter) and real wastewater (return flow from sludge treatment). Within a few weeks a stable biofilm has established. Switching off the microbial fuel cell temporarily doesn't influence the energy output. Therefore the microbial fuel cell can be used for the stabilization of power grids as intended. Different gas diffusion electrodes that contained different types of catalysts (silver, different carbon-based materials) were characterized electrochemically and tested regarding their suitability as cathode in the microbial fuel cell. Gas diffusion electrodes containing silver as catalyst provide the highest energy output. Biofilms that grow on the electrodes have no significant influence on the performance within the first weeks of operation. Additionally it was demonstrated that the cell can be operated without a membrane to separate anode and cathode.

The microbial fuel cell was designed in cylindrical shape and cells in lab-scale and pilot plant scale were built (fig. 1). In this shape the gas diffusion electrode uses oxygen from air and no additional gas flow is needed. The size of the anodes were 400 cm^2 in the lab-scale cell and 2100 cm^2 in the pilot plant. The pilot plant cells were tested in the wastewater treatment plant Steinhof in Braunschweig.

The elimination of micropollutants is a two-step process: First micropollutants are adsorbed on activated carbon. In this step no additional energy is required. In times of excess energy supply the activated carbon is polarized electrically what leads to desorption of the micropollutants. These concentrated substances can be decomposed in the electrolysis cell on a boron-doped diamond electrode. Different porous carbon materials were characterized regarding their adsorption capacity and the most appropriate material was determined. Adsorption and electrochemical desorption of different organic substances were examined. It was demonstrated that the electrochemical desorption is influenced amongst others by the structure of the adsorbed molecule, the pH value of the electrolyte, the potential and the surface properties of the activated carbon. The interaction of these parameters is not yet clarified.

In the case of a stable halogenated x-ray contrast agent the reductive dehalogenation on carbon electrodes was demonstrated. Likewise the oxidative decomposition of these pharmaceuticals on boron-doped diamond electrodes was shown. Several other pharmaceutical ingredients were decomposed as well. The required potentials and electric currents for desorption and electrochemical decomposition differ strongly. Therefore the two process steps adsorption/desorption and electrolysis were separated from each other and will be performed in two different reactors. The modular system can be used as single cells or in combination. Pilot plant cells of both cell types were built and tested in a wastewater treatment plant.

Fig. 1: Two microbial fuel cells were tested in the wastewater treatment plant Steinhof in Braunschweig.

Conclusion

It was demonstrated in lab-scale as well as in pilot-plant that the combination of microbial fuel cell and electrolysis of micropollutants in principle is suitable for stabilization of power grids. However the performance of the microbial fuel cell shall be increased. The potential-controlled adsorption/desorption can be used in various new applications, e.g. the treatment of industrial process water.

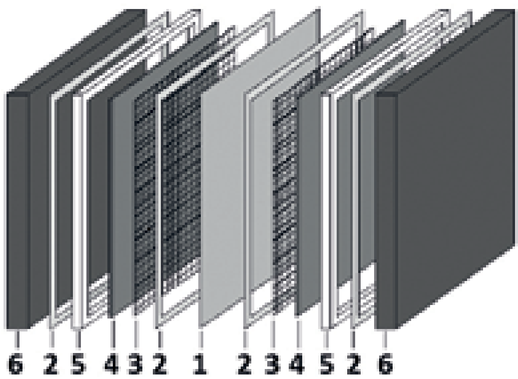

Fig. 2: Scheme of an electrochemical adsorption/desorption cell (1 ion exchanger membrane, 2 sealing, 3 spacer, 4 activated carbon, 5 frame, 6 current collector).

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ENERWA

Energy optimization of entire water supply chains from reservoirs-rivers

Background

Within ENERWA 15 partners from science and practice (water associations, water suppliers, engineering offices) systematically researched energy saving potentials in water supply systems. The main focus was on the dynamic operation of single plants against the background of fluctuating availability of renewable energies and varying energy costs. A dynamic water abstraction from reservoirs was carried out, controlling the water outflow into the lower courses of the rivers and the water utilities in order to exploit the systems to a maximum energetically. Energy saving potentials on the level of plants and subsystems within water utilities and distribution networks were analyzed too. Ecologic and economic impacts as well as legal and societal frameworks were taken into consideration during the studies.

Results

The attempts for dynamisation at a reservoir with strong water level reduction led to a slight warming of the deep waters but the thermal layers and the raw water quality were not affected. The results indicate that a stronger dynamisation positively influences the oxygen levels within the Hypolimnion because the exceeding amount of water outflow deprives the water in the reservoir of nutrients, which in return leads to less biomass that sediments on the ground. A stronger water outflow can even prevent, within certain limits, fine sedimentary deposition and connected negative effects on biocoenosis at the reservoir underflow. The use of already existing dynamic potentials also can improve the ecological status of the reservoir underflow. To reach societal acceptance for a different reservoir management and further possible changes to the water distribution system, additionally to the technical studies a citizen participation procedure was developed and carried out successfully.

It is an option to use drinking water reservoirs as energy buffer within certain limits and there also are flexibility options for water treatment plants and the distribution networks. This includes the targeted use of storage tanks for load management in order to minimize energy costs. But the analyses also show that most of these options would not be profitable for now because of the current electricity price regulations and legal frameworks, especially if investments are needed. A shift in the water outflow from the reservoir for energy production with turbines during the day can be economically useful though, especially in times with high proceeds. A further dynamisation isn't economically feasible right now because of the limited amount of water and the high investment costs for turbines, pumps and storage reservoirs.

A flexible water treatment is economically and energetically only feasible in special cases but it can be useful if it is profitable for other areas of the supply chain. There haven't been any negative impacts on the drinking water quality during the study. The key parameter

Fig. 1: Bigge-reservoir (right) and upstream auxiliary reservoir (left) (Source: Jan Echterhoff, FiW Aachen)

for the water treatment, which had to be limited and monitored, was the turbidity because stronger outflows can lead to the removal of deposits. Flocculation plants too can react to stronger outflows with an increased turbidity, possibly increasing the filtrate turbidity of downstream filters. In order to convert to a more dynamic operation there has to be a technical approach including the typical frameworks for each plant first.

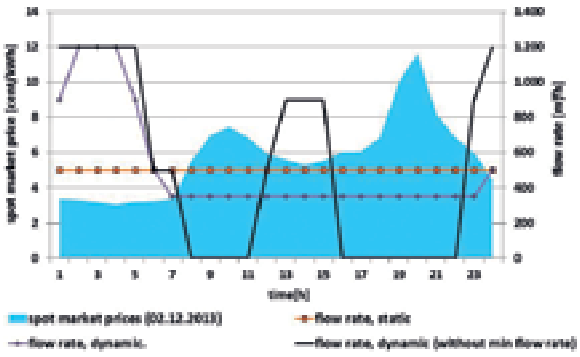

Fig. 2: Dynamisation of the operation of a water company depending on current electricity prices

Next to the dynamisation potential for whole plants there are other efficiency potentials for water suppliers through the technical optimisation of details:

- New optimisation algorithms for water distribution networks have been developed in order to reduce pressure and energy surpluses within the network significantly. The goal is an intelligent grouping of higher-level consumers to new pressure zones. Furthermore, a saving potential of about 300 MWh per year by conversion of pressure reducing valves into small turbines was identified.
- For the drinking water treatment the following saving potentials were identified: prevention of unnecessary pressure head, optimisation of the used dosage of chemicals, dimmable UV-lamps, optimisation of pumps and climate control.

The analysis of the energy saving potentials showed that single optimisation steps don't cause any negative effects on the operation of the other subsystems. The different measures can be combined easily, if the flow rates comply with the purchase- and storage capacities of the supply system.

The legal admissibility of the developed measures is different from case to case but often is given already or easily can be established by changing water permits or contracts. The energy laws are no obstacles but the economic appeal for an energetic optimisation of the water supply system is very limited right now due to energy law funding measures. A flexibilisation of electricity consumption and generation that goes beyond a reduced consumption or an additional generation doesn't appear attractive at this point due to high investment costs.

Conclusion

Energetic potentials could be identified in all parts of the water supply chain, which have no negative effects on ecology, raw water quality of the reservoirs or the drinking water quality. A better utilisation of the increasing proportion of volatile regenerative energy is possible by a more flexible operation of the plants but not economical at this point. If energy prices are rising and/or there is a high fluctuation between minimum and maximum tariffs, many solutions ENERWA offers become attractive on an economic level.

All results have been summarized into an ENERWA handbook that also includes practical web-services for energy analysis- and optimisation as well as information about the developed optimisation tools. It is downloadable under www.enerwa.org and useful for users working in water supply.

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EnWasser

Demand side management in water supply systems for the integration of renewable energy sources

Fig 1: Water treatment plant on the Sipplinger mountain at Lake Constance

Background

The increasing share of fluctuating renewable energies (RES) in electricity generation is already influencing grid operation today. While in the past electricity was generated according to the demand, load management - the adjustment of the electricity consumption to the generation - could make an important contribution to the integration of RES into the energy system. Besides major industrial users, medium-sized plant operators can benefit from price fluctuations on the EPEX spot market as well and realize cost savings in electricity procurement. These include, among others, water suppliers who need electricity to operate their water pumping and treatment plants.

Using the example of the Zweckverband Bodensee Wasserversorgung (BWV), measures for a flexibilisation of water pumping and treatment plants were examined and evaluated. BWV supplies approximately 4 million people in Baden-Württemberg with about 125 million m^3 of drinking water annually, making it the largest water provider in Germany. The raw water is taken from Lake Constance and pumped up to the nearby mountain Sipplinger Berg. Six pumps with a maximum total capacity of 35 MW are available for this purpose. On the Sipplinger Berg, the water runs through several treatment stages with an intermediate water reservoir and a clean water reservoir. In 2014, the costs for electricity procurement added up to 15.5 Mio. €. The project analysed the operation of the current plant and the existing storage in the water distribution grid as well as options for expanding the storage capacities on site (new construction of a raw water reservoir, extension of the intermediate reservoir). In the flexible operation of the system, both the security of supply and adherence to technical, hydraulic and operational boundary conditions must be ensured at all times.

Results

In the investigated water pumping and treatment plant, a previously unused potential for load shifting has been identified and has already been realized in part. It can be assumed that other plants for water supply in Germany have further untapped potential. The construction or extension of water storage capacities allows an increase in the flexibility of the facilities. The position of a water reservoir has a considerably stronger effect on the gain in flexibility than its size. Therefore, storage capacities are recommended to be positioned in a way that results in a decoupling of pumping and treatment. In the case of the surveyed BWV plant, this would be a raw water reservoir, which would not require a large volume, and would be implemented upstream of the treatment stages.

However, the cost savings achieved by electricity procurement on the EPEX spot market are by no means sufficient to fuel investment in storage capacities. The gain in flexibility through additional storage capacity can only provide a contribution margin to the investment costs. Apart from the high cost of building a reservoir, this is because spot market costs account for just below 30% of the total cost of electricity procurement. The EEG levy accounts for 60% of the costs, taxes for 6% and grid charges for 5%. Nevertheless, a detailed investigation of the plant pays off to identify other unused flexibility potentials. In the case of BWV, a change in the operation mode of the existing plant leads to a considerable cost saving in the procurement of electricity on the spot market. A detailed determination and development of the available flexible capacities in the drinking water distribution grid offers further potential for cost savings. Compared to constructing a new reservoir, costs for the conversion of the operation of the systems (for example IT / software and training of the personnel) will be significantly lower.

Significant cost savings can also be achieved with regard to grid usage charges. Cost reductions achievable through atypical network utilization, i.e. the limitation of the maximum consumption of a plant during so-called high-load times, are higher than cost savings achieved through electricity procurement on the spot market along with additional storage capacity. Again, in the case of BWV, the potential of the existing plant has not yet been utilized so far. A separation of the high-powered raw water pumps from the treatment through an additional raw water reservoir, however, enables a further performance and thus cost reduction with respect to the grid usage charges. The various options and associated cost savings are shown in figure 2. The measures described can save a total of 7% of the annual electricity procurement costs, based on historical data on spot market prices, grid usage charges and drinking water demand of 2014.

An analysis of all steps of the water treatment has identified plant components, which prevent a full utilization of existing and potential additional storage capacities, e.g. flow restrictions of filters. An investment to eliminate such restrictions can be more cost-effective than building up new storage capacities. These findings, can be regarded as qualitatively transferable to other water suppliers in Germany. A quantitative assessment of the possible flexibility of plants and associated potential cost savings must be performed in individual cases.

Conclusion

First measures in terms of the improvement in flexibility of the existing plant and the development of available storage capacities, in the case of BWV a flexible operation of the grid storage, can lead to major cost savings in the procurement of electricity. Compared to constructing new reservoirs, only minor costs, e.g. for IT or training of the personnel, are to be expected. A decrease of the maximum load during high-load times would offer further potential for cost savings. A decrease from 19 to 17 MW has already

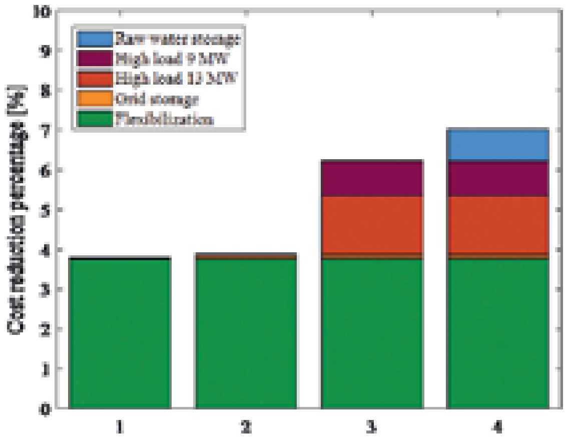

Fig 2: Aggregated annual cost savings in electricity procurement that are to be achieved in dependence of different measures: Flexibility of the existing plant (1) + Management of grid storage (2) + Reduction of max. load in the high-load time to 13 MW or 9 MW (3) + construction of a raw water tank of 40,000 m³ (4). These results are based on data on spot market prices, grid usage charges and drinking water demand of 2014.

been implemented by BWV during the project duration. A heavy minimization of the maximum load at high-load times, however, cannot easily be put into practice in the near future. A further step would be a realization of procurement of electricity on the spot market as well as the implementation of software concerning the optimal unit commitment on-site in order to guarantee the cost-optimal operation of the plant. To successfully implement such software, it is necessary to first analyze the related challenges to the staff, workflow and operational processes and thus create a suitable strategy. The cost savings that are to be achieved through the additional storage capacities on the spot market are not sufficient to fund the construction of new reservoirs. This could change in the future depending on which way the regulatory framework and the market instruments are adapted to the changing energy system in the coming years.

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EWave

Energy management system water supply

Background

Operating water supply systems is complex. It has to be ensured that consumers are reliably supplied with a sufficient quantity and quality of water as well as a sufficient water pressure at all times. In addition to a reliable water supply, consumers demand for reasonable prices. The efficient use of energy has become more and more important.

Within the EWave project, an decision support system has been developed to assist water supply companies with this task. Mathematical optimization methods are used to determine an operation mode at optimal costs. Nowadays, this task is performed almost exclusively by experienced operating personnel as it demands a very good knowledge of the system.

Results

Requirements Analysis/Workshops

A general list of requirements of water supply serves as a basis for the development of a simulation-based assistance system. Therefore, several workshops for water supply companies were conducted. During these workshops, experiences gained with energy management systems were exchanged and further aspects were added to the list of requirements.

Efficiencies

Parameters developed within the EWave project are used to assess the energy efficiency and profitability of a company. This efficiency assessment allows for a comparison of different plants and waterworks. In addition to energy efficiency, hydraulic efficiency was calculated to assess hydraulic plant components. An overall assessment of the plant is realized by calculating the plant efficiency.

Prognosis of Drinking Water Demands

Knowledge about current and future demands for drinking water and energy is a relevant boundary condition for an optimized operation. Energy demands depend on the hydraulic conditions within the waterworks and the entire distribution network of the relevant pressure zone. Therefore, a water demand forecast tool as well as a fully-dynamic hydraulic simulation model have been developed.

The hydraulic simulation model is based on a network abstraction that describes network components, such as pipes, storages, valves, or pumps by mathematical equations and connects them with each other in a network graph. The resulting nonlinear, differential-algebraic equation system is then automatically generated and numerically solved with suitable methods. In order to ensure that the entire water supply network is considered within the dynamic simulation model, network abstraction is necessary. This is realized by combining regional subnetworks to superior pipe and storage elements, thus preserving the large-scale network structure.

Optimization

For decision making and operational support, EWave uses EWave-OPT, a newly developed integrated optimization module. As a result, the user receives operating schedules on a 15 minute scale. For this purpose, discrete-linear, and continuous-nonlinear mathematical optimization methods are combined. First, a mixed-integer optimization model is solved in order to derive all discrete decisions (primarily pump schedules). EWave-OPT uses these results for the discrete optimization variables and subsequently optimizes the continuous variables such as pump speed, valve opening degrees, or water volumes. An energy-optimized operation requires a global consideration of the entire system as well as taking all components into account.

The mathematical optimization methods used by EWave do not rely on already known schedules for pump and system operations. Instead, it shows that this way different pump schedules and additional control parameters can be recommended leading to a more energy-efficient overall operation. Offline optimization results yield a potential of energy savings of up to 10 % for the waterworks in the pilot area (fig. 1).

System Architecture

The EWave energy management system was developed with a modular structure based on existing modules of the SIWA Smart Water Systems by Siemens. In a first step, measurement and operation data are imported and preprocessed. Subsequently, a simulation run is initiated in order to assess the current status of the plant. In addition, the estimated water demand

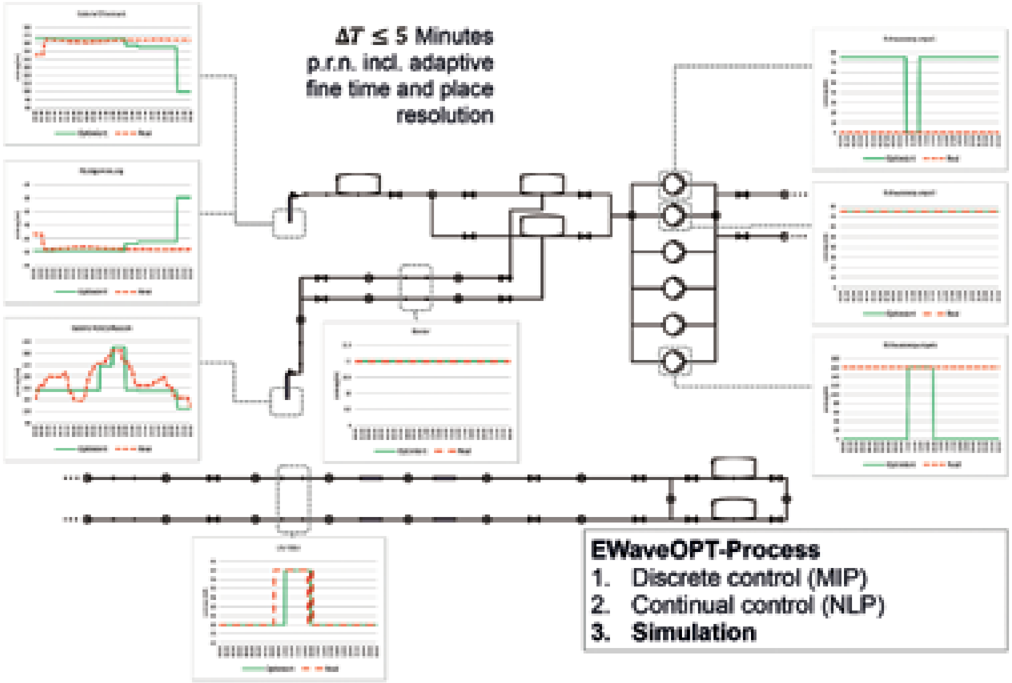

Fig. 1: EWave Calculation Scenario

is calculated. On this basis, the switching times of the pumps are optimized for a preview period of 24 hours. This calculation also takes into account downtimes and operational requirements that may limit the possibilities of optimizing operations within the waterworks. In a final step, the results are validated by a detailed simulation. This process is repeated every 15 minutes.

The results of the optimization (e. g., recommended pump switches and energy costs) and, in particular, a continuously updated list of upcoming recommended switches are displayed to the user on a graphical user interface.

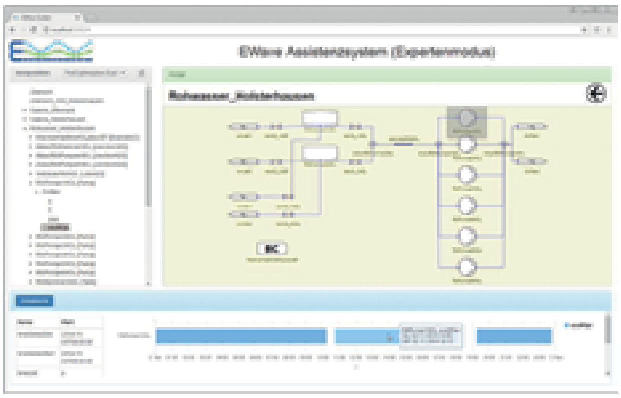

Fig. 2: Web-based EWave User Interface

Conclusion

Nowadays, water supply companies operate their supply systems via automatic systems as well as central control centers. The EWave assistance system calculates pump schedules by adding further information. The aim of this system is an energy- and cost-efficient operation while maintaining a high security of supply. The system has a graphical user interface to visualize schedules, energy costs, etc. A corresponding system documentation as well as an energy and operational data management are the basis for the underlying water supply model of the EWave assistance system. In terms of the supply system considered here, optimization yielded an energy savings potential of approximately 10 %, based on historical data.

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EWID

Energy recovery in the water distribution system by intelligent pressure management

Background

Pressure relief valves (PRV) are used in water supply systems in order to reduce the pressure in the water network and to decrease stress on water pipes. In conventional pressure regulation (by using PRV) energy is converted into sound and heat which cannot be used in the water supply system. The research project „Energy recovery in the water distribution system by intelligent pressure management application (German Abbreviation: EWID)" demonstrates ways to reduce this energy dissipation. For this purpose, a new system consisting of a reverse running pump as turbine (PaT) in combination with intelligent pressure management (ipm) was developed. On the one hand, the goal is to convert the maximum possible energy of the water into demand-oriented electrical energy. On the other hand reducing the supply pressure in pipelines supports the reduction of water losses and material stress in the water distribution network.

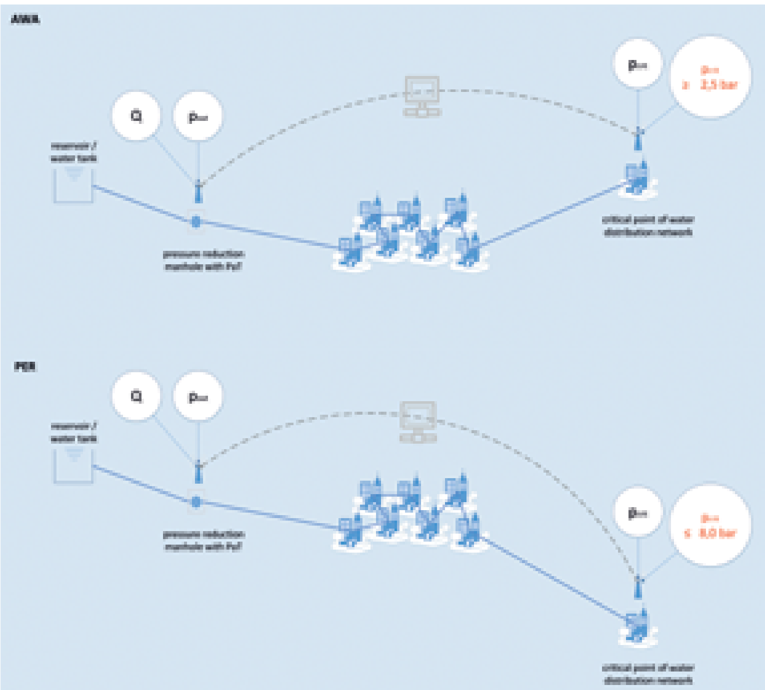

Fig. 1: Boundary conditions and system development PER and AWA; PaT + ipm (UniBwM)

Results

Within the framework of the joint project EWID two PaT application for different water supply networks (Wasserversorgungszweckverband Perlenbach (PER) und AWA-Ammersee Wasser-und Abwasserbetriebe gKU (AWA)) have been tested and analyzed. Furthermore, two energy recovery systems have been developed: network parallel operation for PER and island network operation for AWA. In addition to the reduction of water losses and the material stress, further aims of using the recovered energy can also be pursued: In the case of network parallel operation, an improvement of the overall energy balance is the main focus, whereas generation of additional data of the water distribution network through self-sustaining measuring sensors (e.g. pressure measuring sensors, flow meters) is the main goal during island network operation. Since the installed PaT in the pressure reduction manhole is controlled by a pressure measuring probe at the critical point (intelligent pressure management (ipm)), the location-specific topography has to be included. Critical points, which are identifiable via hydraulic calculations, are, in this context, the points in the subsequent distribution network, at which the measured pressure is most likely to exceed or fall below the value recommended by technical regulations (guaranteeing supply comfort) (see fig. 1).

A pilot plant (flow Q, pressure p) was installed and put into operation at the Universität der Bundeswehr München (UniBwM) in cooperation with the project partners KSB AG (KSB) and Schraml GmbH (SCH) to test the newly developed PaT systems. Within the pipe network a subdivision into three strings was carried out: one for simulating the current state (main string with PRV) as well as two bypasses (secondary strings with PaTs, parallel network and island network operation) which can be opened independently of each other (by magnetic valve (MV)).

First, the network parallel operation system for PER was tested and analyzed. During the pilot tests, four scenarios were successfully evaluated:

- constant outlet pressure (adoption of the PRV task)
- dynamic outlet pressure

- dynamic outlet pressure via critical point by an approximation function that simulates the conditions to the critical point
- Fire load and automatic shutdown of the PaT

Subsequently, the technically more complex system for island network operation for AWA was developed and tested.

After successful pilot plant test runs, the verification in the network, meaning the evaluation of the two developed systems under real conditions, took place. Due to the earlier available results of the network parallel operation, this system (with a different, newly designed PaT) was installed first in PER and was subsequently put into operation, tested and optimized (see fig. 2).

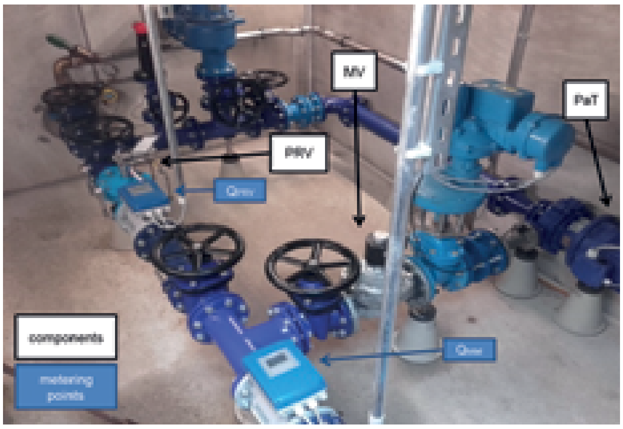

Fig. 2: verification in the network: PER (Original picture: PER, inscription: UniBwM)

The PaT (in the field test: wall mounting, turned by 90° ➛ avoidance of high points) supplements a PRV and is expected to result in a pressure reduction of approx. 7 bar within a flow rate of 6–10 l/s. Test runs with a constant outlet pressure setpoint could be conducted without significant pressure fluctuations and the PaT fed up to 3.5 kW into the local power grid. Further tests with dynamic outlet pressure were also successful. All setpoints can be adjusted in the existing main control system. The system is operated accurately and error-free in network parallel operation. As a further important parameter a critical point in the network was determined, at which the current available pressure is measured and transmitted and which will subsequently be incorporated into the control system via ipm (permissible maximum pressure: 8 bar). This ipm was developed and tested by Dr. Krätzig Ingenieurgesellschaft mbH (KI). After successful completion of test runs at the UniBwM it will be used in the course of the system verification in the water network at PER.

The system for island network operation will be tested slightly time-delayed at AWA, as further test runs have to be carried out at the technical center at the moment. The time delay derives from the more complex circuitry of the individual electrotechnical components and the necessity of a location change for the field tests. The framework conditions of the first-envisioned location did not permit a sufficient volume flow through the PaT and thus inhibited the generation of enough energy for the self-preservation of the system and the energy supply of further measuring probes. The new location meets these requirements. However, this new location is not within the water distribution network and therefore no critical point and no influence on the pipeline pressure due the consumer behavior are existent. Accordingly, no intelligent control of the PaT via a critical point in the subsequent network will be installed at AWA. The outlet pressure will be kept continuously at a low, newly determined value, i.e. the PaT will take over the constant pressure regulation together with the likewise installed PRV.

Conclusion

The systems developed in the joint project EWID (network parallel and island network operation) for energy (recuperation) using PaT are technically feasible and economically viable under appropriate conditions.
Network parallel operation in comparison to island network operation with a standard asynchronous motor lays down lighter requirements on the selection and design of the required power electronics. The critical points, by which the PaT is regulated, have to be identified by hydraulic calculations. Through the installation and operation of these systems, both operational and supply security can be improved. To assure the pressure reduction within the water network the PaT must always be arranged parallel to the PRV in a bypass string. We thank all project partners and associated partners for the successful collaboration. In addition, we would like to express our sincerest gratitude to the BMBF for the financial support of the joint project EWID.

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H_2Opt

Interactive decision support for operation and energy management of water systems based on multi-objective optimization methods

Background

Public drinking water suppliers have to guarantee a constant comprehensive supply of drinking water while maintaining consistent quality. The withdrawals of water from the procurement areas should be done as evenly as possible and in addition, a high energy- and cost-efficiency need to be ensured. Every supply system has its own characteristics and is mostly operated according to experiences. Alternative operation modes are not taking into consideration as not to endanger the continuity of supply. Operators of a water supply system are able to compare different operation schedules to each other by means of the software developed in the joint research project H_2Opt. Moreover they can optimize these pump schedules with respect to energy efficiency as well as a smoother pump operation. Furthermore they can quantify different calculated pump schedules taking into account own criteria.

Results

The operation of different supply systems can be analyzed by means of the software prototype realized within the joint research project H_2Opt. In Addition, the software prototype is able to optimize the operation of the supply system regarding to energy efficiency and smooth operation. The modeling of the system is been done by an interactive drag & drop user interface. The used components of the model, for example pumps and storage containers, have to be specified by sets of characteristic curves (pumps) or geometric dimensions (storage containers). Furthermore the software needs a forecasted consumption for a given time period, for example one day, and the system characteristics of the supply system to calculate different pump schedules by means of numerical optimization methods. Pipeline calculation software has not been used within the joint research project H_2Opt. The system of pipes is been modelled by system curves based in measured data instead. First, this method has been validated at the supply system of the research partner EWR Netz GmbH and following it was transferred to the more complex supply system of the research partner SWK Stadtwerke Kaiserslautern Versorgungs-AG. The system model of EWR Netz GmbH includes the four differently sized main pumps at Bürstadt waterworks, the system characteristics that has been built by means of measured data and finally two identical storage containers. The modernization of the four main pumps, which has been done with the collaboration of the University of Kaiserslautern, has led to a cost saving of 27% (fig. 1). If the main pumps would be operated with respect to minimal specific energy costs, another five percent in energy cost could be saved. Taking into account variable prices of electricity a total potential for cost-savings of 43% could be achieved. Those what-if-scenarios can be done very quickly by means of the software. Technical personnel at Bürstadt waterworks used successfully the software to determine daily pump schedules during the further course of the project. In that case, the software has been tested intensively in practice.

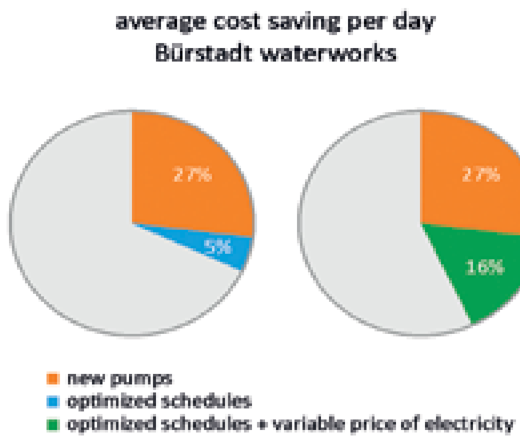

Fig. 1: Potential for cost-savings

The method applied at Worms has been transferred to the supply system of the SWK Stadtwerke Kaiserslautern Versorgungs-AG. The system model includes the four differently sized transport pumps for untreated water at Barbarossastraße waterworks, the system characteristics of the supply area "Normalzone" which has been built by means of measured data and finally two differently sized storage containers. Compared to the pump schedule deposited at the process control system an energy saving of four percent was achieved in a first locally field test. In addition, the total number

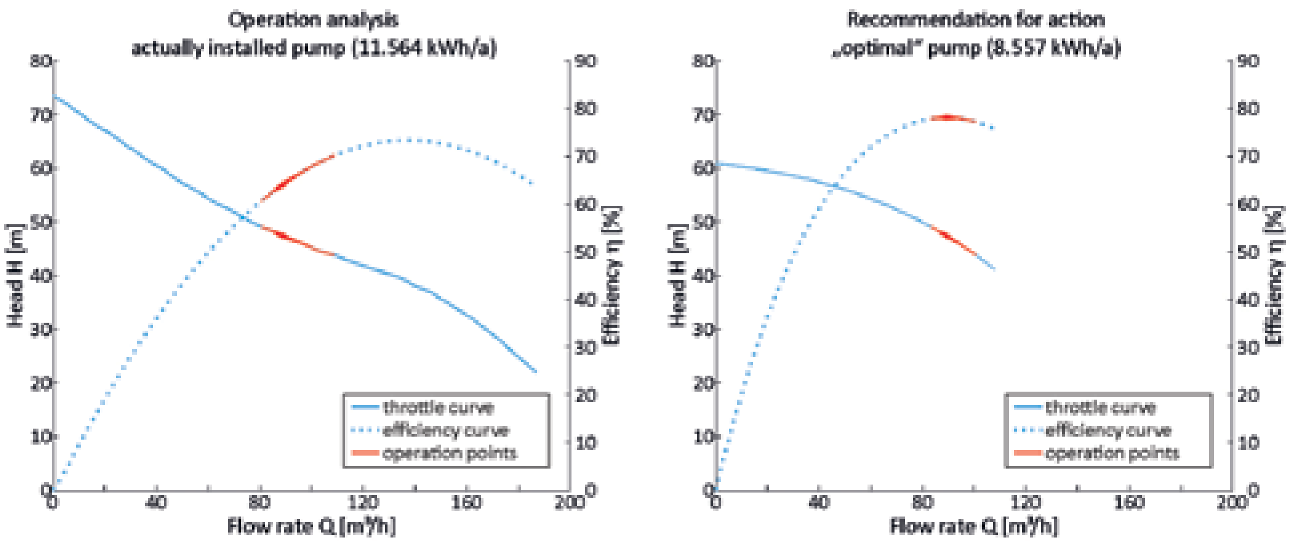

Fig. 2: Comparison of actually installed and newly selected pumps

of switches were reduced from 33 to 7 switches during 24 hours. This reduction has led to a smoother operation of the transport pumps.

During the course of the project a smoother operation has been obtained at the well pumps at procurement are Kaiserslautern East of the SWK Stadtwerke Kaiserslautern Versorgungs-AG as well. This smoother operation was gained by a change of the operating concept of the well pumps. In addition, some well pumps were changed. The decision, which one has to be changed, is based on an extensive operation analysis.

An exemplary comparison of an actually installed pump (left) and a newly selected "optimal" pump (right) is shown in figure 2 over the period analyzed of one calendar year. The installed pump was always operated at partial load over the period analyzed and caused an energy consumption of 11.564 kWh/a. A well pump, adjusted for the application, would be operated optimally and would cause an energy consumption of 8.557 kWh/a which would correspond to an energy saving of about 26%.

Conclusion

The software developed within the joint research project H_2Opt enables an optimization of drinking water supply systems with regard to energy and economic aspects. The achieved results or rather the knowledge gained during the project are very promising. The calculation methods applied to build the system characteristics offer major potential especially for drinking water suppliers that have no calibrated pipeline model. Considerable energy savings were achieved by using the software at both research partners from the drinking water supply. About 6.000 public drinking water suppliers, in the Federal Republic of Germany alone, offer a very high potential for energy savings.

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arrivee

Wastewater treatment plants as control component in intelligent distribution systems with renewable energy generation

Background

The increasing need for a compensation of severely fluctuating power generation is a result of the ongoing extension of wind and solar power plants. These renewable energy sources depend on their naturel availability, which can cause energy network problems by fluctuating energy supply. This is caused by the abandonment of nuclear power and the reduction of fossil-based energy production, which covered a large part of the basic load and the commitment to raise the part of renewable energy to 80% by 2050. As a consequence the impact of renewable energy sources will increase. In case of an energy surplus their input cannot be fed into the energy grid and the generators are shut down. In future, that gap between supply and consumption has to be closed by an additional amount of control reserve as well as storage capacities which could be supported by local water infrastructure management, e.g. wastewater treatment plants (WWTP). The superior function of WWTP is the treatment of (waste-) water which must not be affected in a negative way.

The core objective of the joint research project "arrivee" is the integration of widely available wastewater treatment plants with anaerobic sludge digestion into an optimized control reserve and storage concept. Therefore, the technical conditions of municipal WWTPs, such as combined heat and power (CHP) units as well as gas storage units, are used and enhanced by using innovative technologies. System services are provided with new developed solutions which are necessary today and in the future to compensate fluctuating energy production. Therefore, external influences on the WWTP are analysed and assessed.

Currently WWTPs use the produced digestion gas in most instances for self-sufficiency purposes to reduce the use of external energy sources. Besides the CHP units on the plant, WWTPs are able to switch on or off other energy-dependent aggregates to provide additional flexibility. In the future WWTPs could act as a more active participant in energy grids. Furthermore, WWTPs provide the opportunity to transform energy into a chemical long-term storage matter (hydrogen - H2 and methane - CH4) which can be fed into the natural gas grid and use that stored energy to provide system services in a Power-to-Gas-to-Power concept with multiple synergy effects on (waste-) water treatment and the energy sector.

Results

Within the arrivee project a survey of the national WWTPs with anaerobic sludge digestion has been performed to determine the potential to provide flexibility via electricity production from existing CHP units throughout Germany. The basis to that potential are the consideration of so far unused gas, efficiency improvements on the plants, conversion of WWTPs from aerobic into anaerobic sludge digestion and the use of spare capacities of existing digestion tanks. Moreover, detailed data sets from WWTPs were evaluated to determine the potential in Germany. Results show that WWTPs have considerable potential and meet the required technical restrictions to provide flexibility on energy markets.

An in-depth analysis of significant energy-law relations between the different actors (WWTP, transmission grid operators, and electricity suppliers) was performed. In addition, the current legal and political framework was examined and assessed in regard to the project objectives. With these findings it can be shown that the general political and legal conditions (at the beginning of 2017) are not an obstacle for the analysed innovative technical and operational plant concepts. It is unlikely that the political and legal framework will change in the next ten years in a way that the implementation of decentral flexibility options of WWTPs would not be possible.

WWTPs are capable to provide the flexibility needed, not only with their energy generators but also in terms of their energy consuming aggregates on the plant. Based on evaluated literature and a detailed analysis of aggregates on the pilot WWTP an aggregate management has been developed to shift loads and provide a procedure to identify usable aggregates, characteristic values and control parameters to ensure effluent quality. Even for vulnerable components such as aeration systems load shifting is possible with appropriate control parameters and reasonable time slots, without endangering system functionality. Some of the identified aggregates are tested in real shutdown field trials (on dry weather conditions) at three different WWTPs to verify the model and the actual feasibility of the devices. Flexibility options are implemented in the mathematical simulation model for the pilot WWTP to demonstrate possibilities to participate on different energy markets and providing network services for the

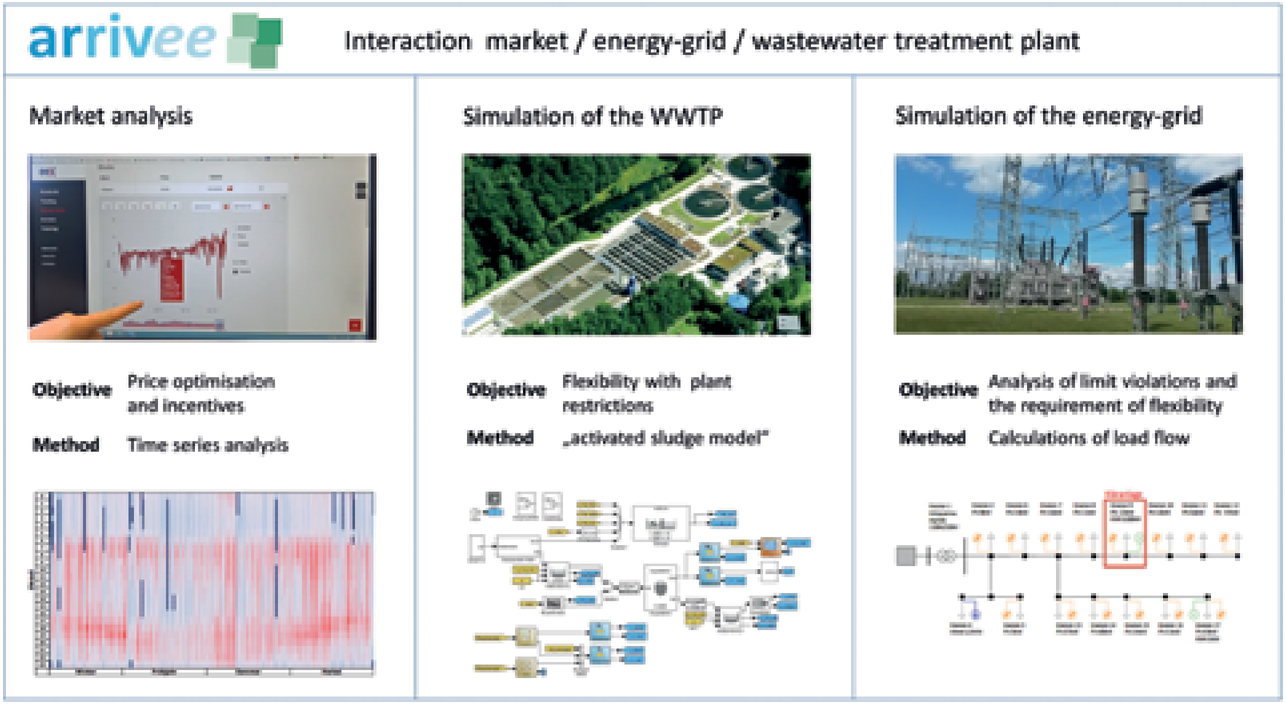

Fig. 1: Objectives and methods of the interaction between market, energy-grid and wastewater treatment plant (Uni Wuppertal/ Stadt Wuppertal)

present situation and future scenarios (2035/2050). Besides the WWTP simulation model the local energy distribution grid is simulated as well. Results of the combined simulations show that the WWTP is able to balance energy shortages in terms of using energy surplus and reduce throttling of renewable energies on the local grid level. This will postpone or reduce cost intensive conventional network expansion. The results of the simulations confirm that the pilot WWTP is able to provide flexibility for different markets today and in future scenarios.

The method of biological methanisation turned out as a suitable innovative plant concept with many synergies on WWTPs. Using energy surplus in the energy grid to produce hydrogen (H_2) and oxygen (O_2) via an electrolyser. H_2 and the digestion gas are used to produce high quality methane (Sabatier-reaction) which can be fed into the natural gas grid. With that plant configuration WWTPs work as a power-to-gas plant and provide long-term energy storage with the additional benefit of producing electric energy with their CHP-units if needed. Furthermore, sustainable synergies result from using O_2 in the aeration systems to save energy or upgrading it to ozone for further treatment in terms of elimination of micro-pollutants. This holistic approach is under actual economic circumstances only possible on a limited basis but may support the role of WWTPs in future as a municipal energy centre.

Conclusion

Results show that WWTPs in Germany are capable to provide the needed technical requirements and potentials to interact on the energy sector and contribute to the German energy transition. The energetic legal admissibility and the political will to implement decentralized actors in electricity, heat and gas markets are ensured but are not a necessary condition for practical implementations. Without economic incentives and further legal certainty plant operators will not enter a hitherto unknown and fast changing market like the energy sector with all their available possibilities. Nevertheless, individual solutions are - under suitable conditions - reasonable and feasible implementations. In addition, the demonstrated potentials and findings are suitable for plant internal utilization like internal (electric) load management. The implementation of Power-to-Gas-concepts will increase the impact of WWTPs as a municipal participant for system services significantly and will show that these plants are capable to operate not only as a consumer, but as a producer of energy on a stable operation of energy grids as well. Many synergies can be created on the plant for the different material flows like the use of oxygen for aeration and hydrogen as a long-term storage option. The dissemination of the gained knowledge and successful practical implementations for this new task of the water management sector is mandatory to move ahead in development.

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E-Klär

Towards the energy-optimized wastewater treatment plant of the future – Development and model-based integration of innovative treatment technologies for transformation processes

Background

The aim of project E-Klär was the development of a method focussing on strategic infrastructure planning for gradual transformation of existing wastewater treatment plants. For this purpose, planning tools were developed and innovative processes investigated.

Results

Using an explorative method with a stepwise approach, a methodology was developed for plant-specific infrastructure planning of robust wastewater treatment plants (wwtp) as shown in fig. 1. The method serves both the strategic planning as well as the decision support for first investments. Decisions are examined under uncertain framework conditions, searching for solutions which lead to good results under favourable conditions, but also provide satisfying results under unexpected developments. Therefore, the evaluation considers both the stability of solutions and their flexibility.

The explorative method is based on a rolling wave planning in a two-stage evaluation approach. In the first stage, future wastewater treatment plants are defined as robust points of reference for strategic development. Transformation pathways – from the current state of a wwtp to its future one – are subsequently derived in the second stage and used to identify investment options. The transformation pathways are evaluated based on indicators characterising the different process chains. These indicators are calculated for various scenarios using the planning tools developed in the project (see below). This information forms the basis for the static, utility-value-based comparison of future wastewater treatment plants and the dynamic assessment of transformation pathways. Both evaluations are undertaken with regard to robustness by cross comparison under different scenarios, whereby the depth of the evaluation is adapted to the available data.

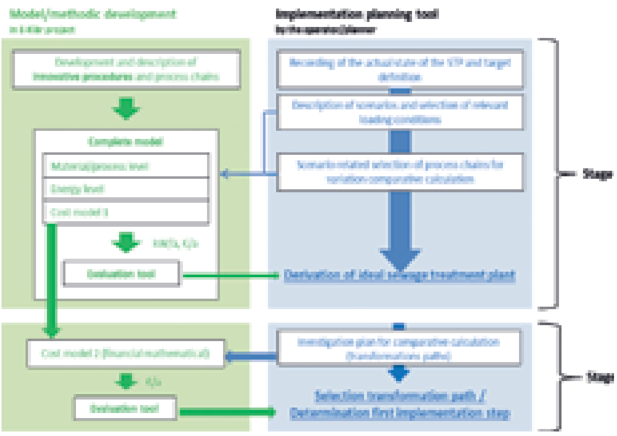

Fig. 1: Overview of the explorative method with a stepwise approach

To transfer the theoretical approaches into practice, the developed methodology was exemplarily implemented for the "Ruhrverband". Planning tools were designed to support strategic infrastructure planning. In contrast to operation controlling, in which real values are recorded by measurements and compared with target values, a "look into the future" is necessary for the implementation of long-term infrastructure planning and requires appropriate forecasting tools. This is reflected both in the level of detail of the used models as well as in the selection and determination of input variables.

One of the developed planning tools is a mass-flow model including energy and cost figures. It allows forecasting calculations of energy and cost indicators for every treatment process as well as for the whole wwtp. Furthermore, based on experimental results (see below) and literature data, information was compiled for each process as a module description. Each module was integrated in the module library of the software WEST and tested. These module descriptions, which are independent of the software, will be published in the final report. To represent the investment pathways, two cost models were developed: (1) cost model 1 to determine annual costs (using the mass-flow model to consider changing design parameters of the treatment processes), and (2) cost model 2 to assess transformation pathways under consideration of financial figures during the forecast period.

In addition to this model, a generator of forecast data was developed, based on the analysis of the current data management of existing wastewater treatment plants of the Ruhrverband. This data generator translates external framework conditions into design-relevant, plant-specific figures using statistical evaluation methods and historic inflow characteristics of the wwtp. These planning tools, together with calculation approaches and statistic evaluation methods were developed and tested on three exemplary plants of the Ruhrverband.

Fig. 2: Screenings wash press and pilot-scale anaerobic reactors with thermal hydrolysis

Innovative processes and technologies were investigated in order to achieve the best possible use of energy and resources contained in wastewater and to reduce the energy demand of wastewater treatment. Screenings' washing, adsorption in a biological two-step process, chemical addition and sieving were used to separate chemically bound energy from wastewater. Large-scale results showed, amongst others, a higher COD-removal with a fine screen (approx. 50%) than in a conventional primary treatment (approx. 33%). Up to 60% of COD were eliminated from wwtp influent using precipitants and flocculants in lab-scale trials. The fibre properties of washed fine screen residuals were analysed in view of resource recovery: Their suitability for paper production is limited because of their fibre length (approx. 0.3mm); other options were highlighted.

For a better utilization of chemically bound energy, fine screen residuals were fed together with excess sludge to digestion, increasing the amount of biogas. Furthermore, excess sludge from different wastewater treatment plants was disintegrated using thermal hydrolysis and digested with primary sludge. Thereby, the methane yield increased (by approx. 20%) together with the nutrient load returned to the wwtp. At the same time, dewatering properties improved significantly (+2 till +8% TS). The use of an energy efficient screw press delivered dewatering results comparable to those of other aggregates when adjusting the polymers. Additionally, a curved screen improved filtrate quality. Experimental results showed that conditioning with biopolymers is possible but requires three to four times more polymers.

For a successful integration of energy efficient nitrogen elimination processes in future wastewater treatment plants, the ASM3 model was extended with the appropriate biological parameters and organisms to describe the deammonification process. Data from large-scale plants with deammonification in the recycle stream were gathered and sludges from these plants were analysed for their characteristics and conversion rate. Process water from thermal hydrolysis processes showed to cause no inhibition in the batch tests performed. On the other hand, condensate streams from different drying plants showed inhibitions of up to 50%.

Design information as well as cost functions were compiled for micropollutants elimination and disinfection processes. Effects of other innovative processes on these final treatment steps were investigated: (1) The addition of chemicals during primary treatment resulted in an additional micropollutants elimination of 0 – 60%; (2) Thermal hydrolysis led to the elimination of some micropollutants, while others were transferred into the liquid phase; and (3) A partial desorption of the contaminants took place during digestion.

Conclusion

The developed methodical and planning tools enable the identification of the optimal transformation pathway as well as the integration of innovative technologies into wastewater treatment schemes for an optimal use of the energy and resources contained in wastewater. The strategic infrastructure planning is conceived as a continuous controlling-process, where selection and evaluation of pathways can be regularly reviewed to take the development of local framework conditions into account.

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ESiTI

Wastewater treatment plant of the future: Energy storage in interaction with technical infrastructure between the poles of energy generation and consumption

Background

Within the frame of the joint research project "Wastewater treatment plant of the future: energy storage in interaction with technical infrastructure between the poles of energy generation and consumption (ESiTI)", the crosslinking of energy flows of wastewater treatment plants (WWTPs) with requirements of the energy sector is investigated. The assessment of diurnal variations of WWTPs' energy consumption and generation with regard to its storage resp. flexibility potentials is the main focus of above mentioned project. Investigations were carried out using the municipal WWTP Zentralkärwerk Darmstadt with its 240,000 population equivalents as example. The objective was to develop measures for holistic energy management, especially with reference to the topic of energy transition. In future, WWTPs will be able to contribute to grid stability in their role as energy service providers.

Results

Within the scope of ESiTI, approaches for the identification, utilization, and optimization of potential flexibilization options for WWTPs have been developed (cf. fig. 1). Presently, results are being compiled in a manual with a focus on sewage sludge treatment as energy consumer, storage and producer. The assessment of flexibilization options is based on the evaluation of energy data from seasonal down to diurnal variations. In addition, capacities of existing energy storage facilities (e.g. storage of substrate, digester gas, heat) are to be identified. Within the scope of project work, requirements from the energy sector have been taken into consideration by developing management strategies. Targeted substrate and load management by WWTP operators facilitate, for example, reduction of required grid capacity (balancing of diurnal variations), improvement of grid stability (control energy) resp. reduction of their own costs by using dynamic electricity tariffs contributing to balanced residual loads.

The investigated strategies can be implemented using measures in the field of storage management and energy consumption resp. generation. Besides the utilization of existing redundancies in process technology and mechanical engineering, innovative potentials using co-substrates, thermal pressure hydrolysis, and digestion (conventional / high load digestion) were investigated using laboratory and pilot scale plants. Generation and utilization of digester gas in combined heat and power units (CHPs) are key elements of needs-oriented supply of electricity and heat.

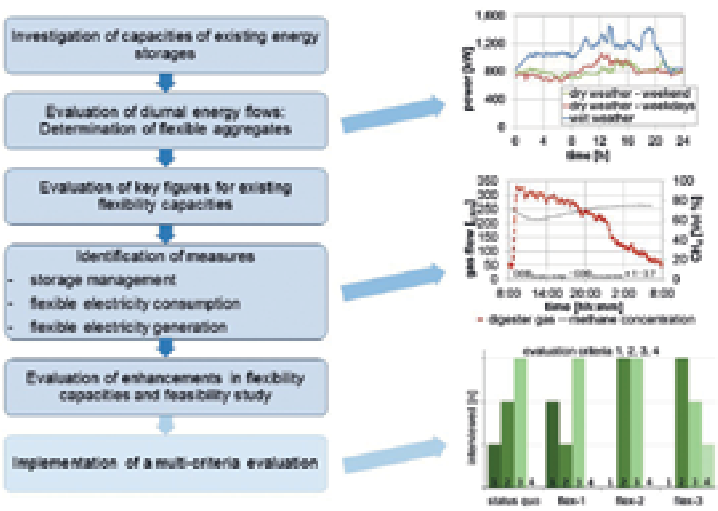

Figure 1: Scheme of the manual on flexibility enhancement

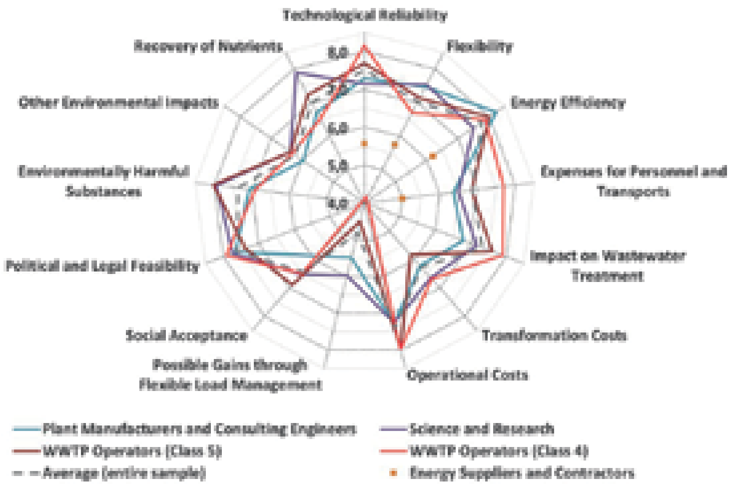

Fig. 2: Weighting of assessment criteria by interviewed WWTP operators

Via flexible operation of digester gas producing sewage sludge treatment plants in combination with flexible power generation (conversion of generated digester gas into electricity in CHPs), the demand for energy storages can be reduced significantly. For flexible power generation, however, a holistic approach regarding other energy flows, e.g. (waste) heat, is necessary, requiring intelligent heat management. In addition, future requirements, e.g. by including thermal sewage sludge treatment, have been considered. Consequently, heat utilization, power generation, disposal reliability and phosphorus recovery have been investigated.

Through utilization of co-substrates, the external energy demand can be reduced significantly and therefore the environmental impact for WWTP operation. However, in case alternative substrate management (e.g. digestion in a neighboring biogas plant including agricultural use of fermentation residues) is used as benchmark, results may differ depending on the environmental impact of the respective alternative utilization path. Against the background of crosslinking with the overall energy system, flexible operation of CHPs (subject to the structure of the power station facilities) enables savings in CO_2 emissions. Here again, the capacity of energy storage, e.g. gas storage, is decisive.

Finally, within the scope of ESiTI, a multi-criteria assessment study was carried out on different management strategies for future WWTPs, using economic, ecological, technological, as well as socio-political criteria (cf. fig. 2).

Conclusion

The requirements of the energy sector for flexible energy producers resp. consumers include flexible load management at WWTPs by combining different facilities. The former approach of improving the efficiency of individual units by energetic optimization is not sufficient any more, and has to be supplemented by the holistic approach on flexibilization potentials. Besides considering technical parameters on diurnal variations of electricity and heat consumption, it is also necessary to look at environmental impacts and socio-scientific aspects. The manual, elaborated within the frame of ESiTI, addresses operators of WWTP and brings all results together presenting possibilities and limits of flexible management and operation.

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KRN-Mephrec

Transforming sewage sludge into energy, fertilizer and iron in a single process step

Background

Sewage treatment plants in Germany treat approx. 10 million m³ of sewage per year, producing 7.5 million m³ of dewatered sewage sludge which today is spent as waste in agriculture or it is burned. Wastewater treatment is laborious (about 4,400 GWh per year of electricity consumption) and it costs around 6 billion EUR per year. With new technology and process changes, wastewater can be used as a source of raw materials and to a great extent the recovered energy can be used to meet the energy requirements of sewage treatment plants themselves.

According to the new sewage sludge ordinance, large cities have a period of 12 years to implement a process that will recover at least 50% of the valuable phosphorus contained in the sewage sludge and thus to cover an amount of up to more than 40% of the German phosphorus requirements. Among the practice-relevant processes, thermal processes with higher recycling rates of over 80% are favored in order to utilize the energy contained in the sewage sludge and to render the residual materials harmless.

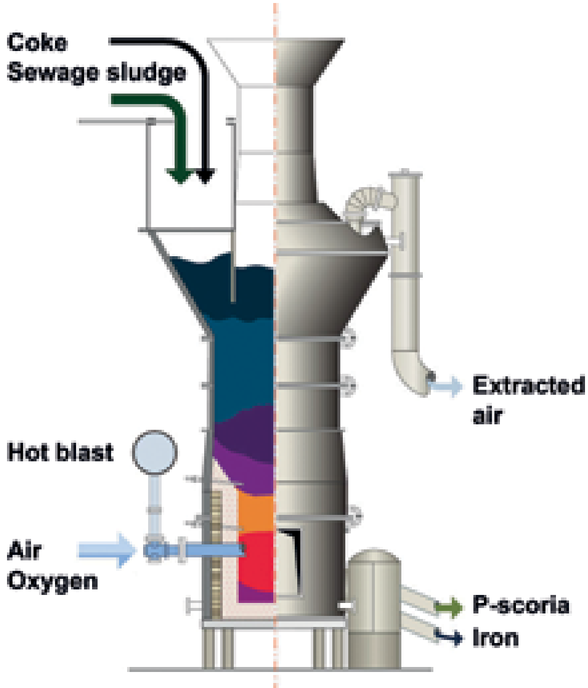

Fig. 1: Cupola furnance

The sewage sludge market has a potential of at least 1,000,000 Mg of dry mass per year with a financial requirement of more than EUR 500 million per year. So far, there is still no established, economically viable process to meet the new requirements. Therefore, it is necessary to prepare, test and make process-related and operational concepts available on an international level for large plants.

A procedure derived from smelting technology was tested in Nuremberg for this purpose within the framework of the joint project KRN-Mephrec, Nuremberg Region Sewage Sludge Utilization with Metallurgical Phosphorus Recycling. Using so-called melt gasification, dried and briquetted sewage sludge is melted in a melting furnace at temperatures of up to 2,000° C and the valuable resources from the sewage sludge are recovered as with iron production.

Results

The process is being thoroughly tested on a scale of 1 to 5 at the Nuremberg sewage treatment plant. Production with sewage sludge drying and briquetting was developed. In addition to sewage sludge, monocombustion ash is also processed into stable briquettes with a long shelf life. In preparation for melting, a differentiated mixture of sewage sludge briquettes is produced together with foundry coke, limestone and, if required, other rocks.

The precisely weighed batches are fed into the melting furnace via a sluice and these batches are stacked at a height of about 3.50 meters. The closer the batch gets to the melting zone, the more the sewage sludge is heated. The synthesis gas which is formed here emerges as a furnace gas at the shaft head and it is then burned in a chamber in the test plant. The synthesis gas is to be purified later during an additional process and then made available on an industrial scale for power and heat generation.

The rocks and sewage sludge begin melting at around 1,600° C within the actual melting zone. The temperature is reached by burning a portion of the foundry coke and by blowing in hot air as well as technical oxygen above the nozzle level. The remaining portion of glowing foundry coke forms the supporting matrix with gas flowing through. The pore space in the lower part of the furnace fills with liquid slag. At the bottom of the reactor, the heavier liquid iron collects along with all the precious and heavy metals contained in the sewage sludge. The liquid slag collects over the iron bath.

The slag exits the furnace continuously via a discharge hole and it is subsequently granulated in a water bath. In further steps it is ground inside a ball mill and is granulated to form spreadable fertilizer. The iron melt is filled into a mold by briefly opening the discharge hole at the floor level of the reactor. The solidified iron is recycled to the steel industry.

The business partner Baumgarte Boiler Systems GmbH established the core components of the test facility according to the specifications of the process provider Ingitec GmbH. Nuremberg Region Sewage Sludge Utilization GmbH provides the other components for the process and manages the test facility as a municipal development measure in the sense of the new sewage sludge ordinance. The business partner Innovatherm GmbH brings in experience as the largest monocombustion plant operator in Germany. The sewage sludge ashes are treated in a separate series of tests.

The Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT located in Sulzbach-Rosenberg makes a balance of the process chain and develops the recycling concept for the synthesis gas which is produced.

The IFEU Institute in Heidelberg prepares the ecological balance for the entire process chain and compares the process with alternatives for sewage sludge utilization.

The Institute for Water Supply Management at RWTH Aachen determines the quality of the products and compares this with other recycling processes. The German Armed Forces University in Munich clarifies the integration of the process chain into the sewage treatment plant and takes care of the wastewater-related issues of the process. The regional marketing concept for recycled phosphorus is developed with the participation of experts.

The metallurgy of shaft furnaces is a century old tradition. Nevertheless, applying this technology to sewage sludge is still a major challenge. With a melting capacity of approx. 400 to 450 kg / h the smelting furnace which has been built is more efficient than calculated and the resulting gas quantities are not easy to handle from a technical standpoint. The existing exhaust gas treatment system and certain components had to be modified several times or retrofitted. Hence, the many investigations by scientific partners have not yet been concluded.

Control of the process proves to be demanding in terms of the doses of substances, as well as the air and temperature control. Nevertheless, the technology is promising in

Fig. 2: Slag discharge during the first melt test

terms of reaching the targets of a material and at the same time energetic utilization of sewage sludge without residual waste and in an economically viable manner and it will therefore be tested and further developed technologically through additional tests. Process control, especially with regard to gas generation, purity of the products and energy consumption, will continue to be tested and optimized.

Conclusions

As an alternative to monocombustion the metallurgical conversion of sewage sludge into metal and phosphorus slag is a particularly promising process, which is workable, sustainable and at the same time financially viable. Recovery of the products is particularly high (over 80% of the total phosphorus). The method is particularly efficient and compact because of its one-stage operation. The Mephrec method is particularly advantageous in terms of its efficiency and it produces virtually no waste.

The synthesis gas which is produced can be reused, for example for combined heat and power unit use. As a recyclate the resulting phosphorus-rich slag is further processed mechanically into a fertilizer with medium and sustained fertilizer effect. It is very low-polluting and has good prospects to prove itself in agriculture due to the low cost supply. The tapped metallic alloy goes to the scrap metal trade.

If the first test results have been confirmed and the technically required individual components for a large plant have been clarified within the framework of the pilot project, following thorough economic feasibility studies a large-scale plant may be established, which can be process up to more than 70,000 Mg of sewage sludge per year.

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