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Integrating local solar energy and water recovery: operating experiences of a systemic approach

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ABSTRACT

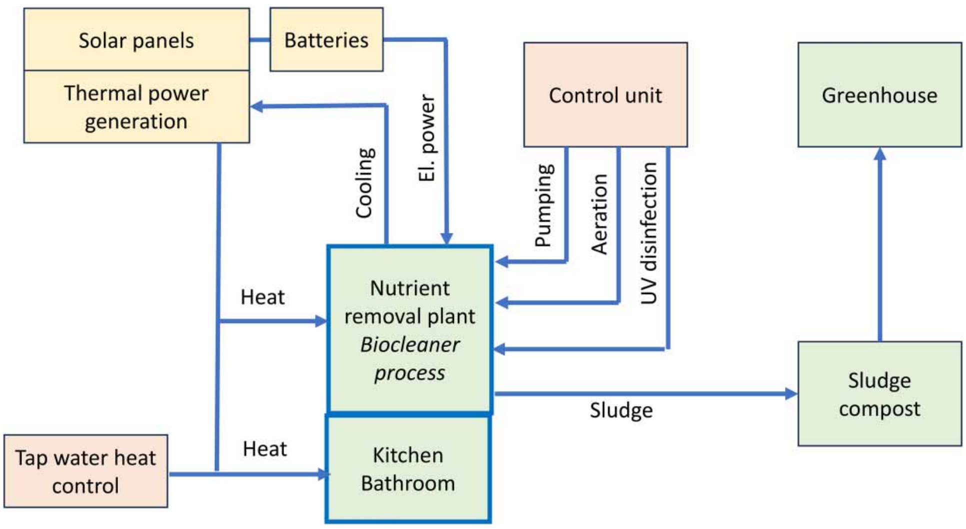
The key message is the importance of a systemic approach to handling water and energy together, both in design and in operation. The paper demonstrates how renewable energy, solar photovoltaic (PV) and solar thermal, in combination with a small nutrient removal plant provides a reliable solution for small-scale decentralized water recovery operations. The system is automated and can operate outside the power grid and is designed to be a fully circular system in terms of both energy and water. The system has been installed on an island in the archipelago outside Stockholm, Sweden, to replace an old-fashioned septic tank. The effluent must satisfy rather strict effluent quality criteria for the Baltic Sea. The paper describes design considerations, instrumentation aspects, automation features, and operation experiences.

Key words: automated water resource recovery, circular resource recovery, decentralized water resource recovery, solar energy, Sweden, systemic approach

HIGHLIGHT

- The key message is the importance of a systemic approach to handling water and energy together, both in design and in operation. The paper demonstrates how renewable energy, solar PV and solar thermal, in combination with a small nutrient removal plant provides a reliable solution for small-scale decentralized water recovery operations.

GRAPHICAL ABSTRACT



INTRODUCTION – AUTOMATION DEVELOPMENT DURING HALF A CENTURY

In 1975, the two of us implemented the first computer control system at a full-scale wastewater treatment plant in Sweden and presented at the 2nd ICA conference in London in 1977 (Gillblad & Olsson 1977). During this nearly half-century, there have been remarkable developments in process technology, process understanding and modelling, instrumentation, computer systems, communication, control, and electric power generation (Olsson 2012; Olsson *et al.* 2014). Today we can create completely new solutions and structures. Decentralization of water resource recovery is one important aspect.

The technological development may be described as a democratization of technology. Processes, control systems, computers, and energy generation are now scalable and can be made efficient and affordable even at the household level. This has created a completely new perspective on how to realize both water supply and water resources recovery. Process supervision is available and affordable for individual users. For example, today all sensor information, including alarms, equipment status, state of consumables, as well as other sensor information can be presented on a smartphone (Larson 2022).

One essential consequence of decentralization is that grid-connected sewer systems (except stormwater draining) are not needed, contributing to economic flexibility, faster innovation, and allowing tailoring of water quality for the user (Bajpai *et al.* 2019; Rabaey *et al.* 2020).

Here we portray the operating experiences of a small integrated water resource recovery system for a single household using up-to-date, affordable, and adequate processes, energy supply, and information technology. The biological treatment includes carbon, nitrogen, and phosphorous removal. The system design is completely circular in the sense that it does not require any external input, except chemicals for phosphorus precipitation. Electric and heat energy are provided via solar panels. Local handling of household wastewater typically involves various forms of maintenance, such as collection of sludge, and infiltration of used water. These aspects are also discussed.

The concept and potential advantages of decentralization have been discussed for decades (Orth 2007; Massoud *et al.* 2009; Larsen *et al.* 2013; Singh *et al.* 2015). The development of process technology in combination with automation technology during the last decade has resulted in major progress. Today a fully decentralized activated sludge process can produce an effluent quality that by no means is inferior to large-scale treatment plants. Not only the processes have been decentralized but also the energy production.

Solar photovoltaic (PV) is today a superior electric energy source from an economic perspective. Moreover, it is scalable from household size to municipal size. Solar PV-powered water systems have been in operation for many years. Desalination process applications are applied extensively (IEA-ETSAP & IRENA 2013; Shatat *et al.* 2013; Cipollina *et al.* 2015; Mahmoudi *et al.* 2017). Solar-powered pumping, particularly for irrigation, is described by Rahman & Bhatt (2014), Campana *et al.* (2015), IRENA (2016), Sontake & Kalamkar (2016), Chandel *et al.* (2017), and Islam *et al.* (2022). Olsson (2018) contains further information.

Strazzabosco *et al.* (2019) assessed the current status and opportunities of solar PV adoption across wastewater treatment plants of different sizes in California. When applied, solar PV was a complementary power source to the grid power. Colacicco & Zacchei (2020) have proposed, but not implemented, solar PV to power aeration tanks in activated sludge plants. Pandey *et al.* (2021) review trends in solar PV applications for wastewater treatment. UNDP is supporting an ongoing project in the Gaza Strip called 'Photo voltaic solar system for the Rafah wastewater treatment and reuse plants' (UNDP 2023). Solar PV will provide 100 kW of peak power to operate the plant and another 100 kW of peak power for pumping.

To the authors' knowledge, water recovery decentralization combined with solar power, outside the grid, has not been proven in extended practical implementations. This describes that it works in reality. Two contributions are emphasized:

- The systemic approach to solar PV connected to the biological water recovery system. The system is completely self-supporting, outside the power grid, and without any sewer system connection. The design and control of the activated sludge process is state of the art, and the process is considered only part of the complete self-contained system.
- The system has been in operation successfully, without any interruptions, for 3 years in a relatively cold climate. It also demonstrates that downscaling in size to a household level can be realized successfully with no effluent water quality sacrifice.

THE PROCESS

The water recovery process is a commercial system BioCleaner (Envi-Pur 2023) designed as a pre-denitrification system for nutrient removal (Chen *et al.* 2020). The treatment system is contained in a plastic tank with a 1.6-m diameter built into a small housing made of hollow concrete blocks (Figure 1). The process is designed for one household (up to 5-person equivalents, pe), but there are commercial units up to 50 pe. Insulation is complemented with 10 cm plastic foam blocks. The walls provide heat insulation, so the microorganisms can be maintained at an appropriate temperature. The unit is a complete mini wastewater treatment unit, built in sections. The BioCleaner process has been installed in several hundred places and has been approved by regulatory authorities. Notably, the process manufacturer has not before connected to this system with solar energy.

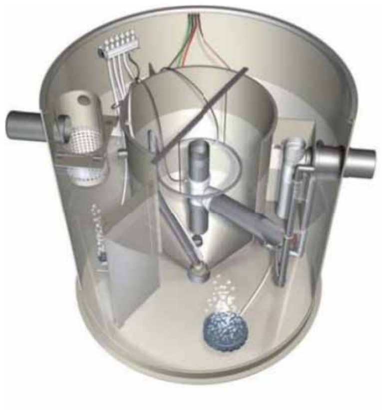



Figure 1 | The BioCleaner process and the current installation. *Sources*: left picture, envi-pur.cz and right picture, author.

The process is continuous, and the influent flows down into a plastic tray, serving as a screening unit. Air is provided at the bottom in a vortex strong enough to break bigger objects like toilet paper into smaller pieces. Iron sulphate is added to the denitrification zone for simultaneous phosphorous precipitation. The chemical dosage is automated, where a micro-pump is dosing iron sulphate proportional to the water flow rate. At the bottom of the anoxic zone, there are aerators providing large air bubbles aimed to mix and still avoid aeration. The water is then led into the aeration chamber, supplied with a fine bubble aeration system. A digital controller maintains a desired retention time in the anoxic and aerobic zones, depending on the influent flow rate. The effluent water is passed through an ultraviolet (UV) lamp for disinfection.

The sludge level changes very slowly and is monitored manually infrequently – only the order once every few months – by a stick with a white area indicating the level. When exceeding a predetermined level, the sludge is pumped out with a portable pump (a typical volume is 15–20 l). The sludge is composted together with garden greens. If floating sludge would appear, then the sludge is decanted and brought back into the settler zone. An interesting feature of the

The guaranteed design effluent quality parameters are BOD $\leq$30 mg/l, N-tot $\leq$40 mg/l, and P-tot $\leq$1 mg/l. The regulatory agency is interested only in effluent P, which has been typically around 0.5 mg/l during 3 years of operation. Given the high standard of the effluent quality of the mini treatment plant, the effluent can, for example, be infiltrated or used in a greenhouse. The composted soil can also be applied in the greenhouse. Today no effluent water flows into the sea.

The process does not have any moving parts, which contributes to high reliability. There are no mechanical pumps. Instead, all water movements are realized by producing pressurized air and injecting it into the pipes. This kind of water pumping has been optimized for a certain pipe diameter, so the scalability of the pumping must be carefully calculated to make the pressurized air pumping work for different flow rates. Thus, water pumping with pressurized air is realized for processes up to 50 pe, but for larger flow rates mechanical pumps are required, so upscaling is not trivial.

ELECTRICAL AND HEAT SUPPLY FROM SOLAR PANELS

The whole system is driven by a solar-powered unit. The solar PV panels are designed as regular roof tiles using a 3D printer (Figure 2). This provides around 120 W/m^2 and 24 VDC. The electric power consumption is about 60 W (depending on the influent load), so only a few roof tiles are required for power generation.

Figure 2 | Roof with solar panels and thermal power generation.

Obviously, the solar PV system generates electricity only during the day. However, two conventional car lead batteries can provide more than sufficient power during the night, even in the winter.

The sun provides not only electric power from the solar PV panels, but also generates heat from the panels, up to the order of 600 W/m^2. Future plans include heat storage (see below) that will provide the mini-plant with sufficient heat energy to operate satisfactorily even during cold winter days. This heat is taken care of by circulating antifreeze agents in channels below the panels, needed for the coldest winter days. As a bonus, by circulating water, the system will cool the solar PV panels and consequently increase their efficiency while providing heat for the process.

It should be emphasized that the solar PV energy received depends on the angle of the solar panels. However, the heat energy absorbed by the solar rays is independent of the angle of the panels.

CONTROLLING THE ACTIVATED SLUDGE PROCESS

The paper only describes some specific features of the operation, since activated sludge control is a known technology (Olsson & Ingildsen 2020). The control can adapt to the load by varying the airflow to the aerator from running 5–10 min/h up to the continuous operation, providing a control authority min/max of about 1:9. The current installation is not equipped with any DO sensor. Instead, aeration is driven based on the influent flow rate (Figure 3). It is apparent that a large treatment plant with DO control will have a higher air supply energy efficiency. However, given renewable energy from solar PV panels, energy consumption is not a major issue. It is more a matter of using available energy as wisely as possible. From a microbiological perspective, it is important to balance the air needed by the aerator in order to limit the development of, for example, filamentous organisms. Note that the system does not provide any by-passing.

SOLAR ENERGY CONTROL SYSTEM

The operation of the activated sludge system is driven by 24 V DC, so there is no need for any DC/AC converter. However, the current UV lamp is to be supplied by AC.

The controls are made using a standard PLC structure in a unit supplied with an intranet connection for operator information. The control unit has been produced using a 3D printer (Figure 4). This is a true low-cost device. The system can be remotely controlled via a 4/5G modem, getting a copy of local data from the controller via a standard industrial protocol. The data can be presented in a standard mobile smartphone. Also, alarms can alert the owner via a smartphone.

Figure 3 | The commercial control unit for the airflow valves, driven by 24 V DC.

Figure 4 | A control unit, produced in a 3D printer, based on Raspberry Pi.

OPERATING EXPERIENCES

It should be emphasized that the system design is optimized for this scale. Most importantly, moving the water depends primarily on the compressor's capacity to produce air bubbles to move the water. This in turn depends significantly on the water pipe diameter.

The system has been in operation for 3 years with no operational interruptions, even during the coldest winter months.

The solar panels have generated heat 10.5 months out of a full year at the Stockholm latitude.

Effluent quality is measured biannually by taking samples to be analysed in the laboratory. So far, the design of the sizes of the different water sections in the unit has proven to follow a model that gives excellent water treatment results based on a treatment model suitable for small households. The system is an example of the fact that technology, previously only available in large installations, can now be scaled down to fit a household budget.

CAPITAL AND OPERATING COSTS

The downscaling process usually means higher capital and investment costs. This is not necessarily true for the system in consideration. Comparing investment costs for a centralized municipal treatment plant and a small household-size plant also should take sewer costs into consideration. This treatment system, including the energy supply and designed for 5 pe, has an investment cost of SEK 50,000 (€4,300)/pe. A municipal treatment plant for a relatively small community in Sweden will cost about SEK 10,000 (€860)/pe, excluding the sewer network. Depending on the population density the *total* investment cost will be of the order 30,000–40,000 (€2,600–€3,400)/pe. The operating cost for a centralized system also must consider pumping costs for the primary influent. It seems probable that distributed solutions can be cost-competitive for small municipalities. Obviously, the first installation of a system like this one is more costly. The cost can be considerably reduced with standardized solutions.

Operating statistics of the activated sludge plants of the type in this installation show that the electric energy demand is around 220 kWh/year for 4–5 pe, indicating an average power requirement of 7 W/pe.

One solar panel can produce 10 W. However, it is required to produce 60 W in certain time intervals, since the pump operates discontinuously. To produce the electrical energy, we use eight solar panels. They must be serially connected in order to obtain sufficiently high voltage, 24 V DC. The eight solar panels can produce around 400 kWh/year, supplying the electric power from a roof area of around 1 m^2.

FURTHER DEVELOPMENT OF AN INTEGRATED ENERGY – WATER SYSTEM

The integrated concept has been proven to work satisfactorily. The existing system is the first step in a larger integrated system, and further enhancements are planned.

Since the energy is free in a solar PV system, the challenge is not to save energy but to make the most efficient use of surplus electrical and heat energy. How to make use of it naturally depends on the geographical location, the household size, and many other factors. In a rural area, outside the power grid, there are several options (Olsson 2018) like pumping groundwater and storing it in a hydrophore, or pumping water for irrigation.

A heat pump is an important and integrated part of the total system. Excess electric energy can be converted to heat in an air/water heat pump. The heat pump can control the water to the desired temperature. The next phase of the project is to control the antifreeze water flow rate based on the heat flow using a variable speed pump, powered by solar PV. The heat flow is led through a newly designed heat exchanger that operates like a heat flow sensor with a very short time constant (Figure 5). The initial purpose of the heat exchanger has been to recover heat from warm water in showers. This heat sensor makes it possible to dynamically control the heated water flow, providing the biological processes with sufficient and adequate heat energy.

Figure 5 | The shower floor heat recuperation system. *Source:* https://joulia.com.

The system also works as a solar heating system to provide the mini-plant with sufficient heat energy to operate satisfactorily even during cold winter days. Water from the heat pump is stored in a tank. The stored hot water from the tank is used as warm water in the household and then passed on to the activated sludge process. The panel area on the roof is not big enough to generate a surplus of heat, but excess warm water not used in the household is used to increase the temperature in the treatment process.

LESSONS LEARNT

Scalability is a major issue that must be considered carefully. It is obvious that solar PV and solar heating are scalable to any size, and the complexity does not depend on the system size.

As remarked, the water flow rate control is not easily scaled. Since the water flow is driven by air bubbles from a compressor there is an optimal relationship between flow rate and water pipe diameters.

Measurements of the sludge level and sludge removal are not automated. These operations are made so infrequently that it would be overkill to automate them. Generally, it is always important in any system how far to implement automation.

The system is an example of a circular water and energy economy. There is no external source of electrical and heat energy. No effluent water flows into the sea but is infiltrated or used for irrigation in the greenhouse. The sludge is brought (manually!) to composting for later use in the greenhouse.

The key lesson from this installation is that large-scale design and operation can be avoided when not necessary. In this way, it is possible to maintain a simpler structure of the system. Furthermore, all parts of the energy-water system can be standardized and mass-produced. This is a democratic application of high-tech design, control, and operation.

The operational experiences so far tell us that the probability of a system failure is very low. If the energy is shut down for weeks or longer, then the process will work as a septic tank. At least organic carbon will be removed.

CONCLUSIONS

A systemic water and energy approach to designing and operating a household-size treatment plant is described:

- The design of an activated sludge process in the household scale works reliably and satisfactorily with a minimum of maintenance and operational problems.
- The energy requirement for the process is readily provided all around the year with few solar PV panels. The system has operated reliably in a cold climate for 3 years. Therefore, the authors are confident that a similar system will work satisfactorily in any other region, particularly considering that it can operate outside the electrical power grid.
- By extracting the heat from the solar panels there is a double gain: cooling the panels will increase their electric power efficiency, and heat can be provided all around the year also in a cold climate.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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