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S2E – Sludge To Energy

Executive summary

The paper industry has historically managed resources in a linear logic: cellulose enters the process, paper comes out, and, with that, tons and tons of waste are disposed of. It can be estimated that up to 16 million tons of sludge are produced globally each year (Turner et al, 2022). What if that waste could instead get a second life by transforming into useful green energy? The Sludge-To-Energy project, or "S2E", tackles this challenge by providing an innovative system able to convert organic matter into electrical energy. The sponsor and client of the project is Fedrigoni S.p.A., leader in the paper production industry, that wants to be pioneer of innovative waste-to-energy solutions.

The objective of the research is to understand if the organic sludge can be recycled in order to extract energy from it in a sustainable way. For the purpose, experts were interviewed, and different laboratory analyses were conducted. This approach let the team achieve noteworthy results:

A. The paper sludge proved to hold a great energetic potential. In particular, the *Fabriano* paper plant will be home of the first pilot system, which is estimated to produce over 200 kW of continuous electrical power.

B. The project was found to be economically sustainable, with an estimated payback time of 10 years, over a plant lifetime of 20 years. This is due to the revenue streams coming from the sale of the produced green energy to the grid, together with the avoided costs deriving from a reduction in the amount of waste that would be disposed of in an ordinary way.

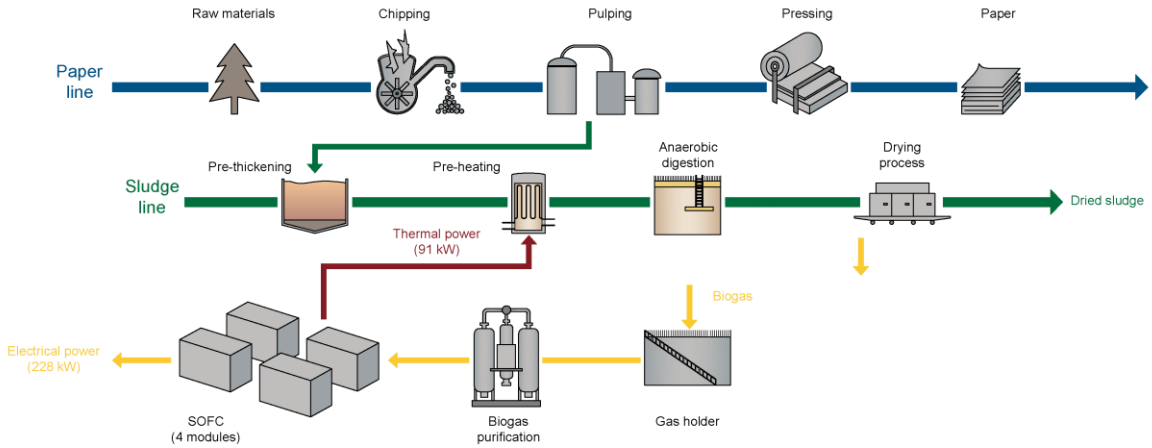
C. From a socio-environmental point of view the project proved to be impactful as well, encouraging the creation of new jobs and increasing the renewable energy quota available within the national grid.

These results achieve even greater importance if combined with the originality of the project, which is twofold: to the best of our knowledge, (i) no SOFC application for paper mills's sludge has ever been conceived, and (ii) the S2E project would become the largest industrial biogas-powered SOFC plant, at international level.

Key Words

Waste, Paper, SOFC, Decarbonization, Circularity

FEDRIGONI S.p.A.: paper producer, sponsor and main client of the project.



The proposed final S2E solution: Fabriano paper mills sludge is converted into biogas through anaerobic digestion, then filtered and finally transformed into electrical energy through four SOFC modules.

BTS Biogas: Biogas treatment company, S2E and Fedrigoni partner for developing an anaerobic digestor.

Project description written by the Principal Academic Tutor

Biogas could represent one of the most interesting sources in the present and future energy domain. Several reasons behind that:

(a) it is a fuel of biological origin, then sustainable and C-neutral;
(b) it is recovered from waste organic material, then reducing the needs of waste disposal and generating a positive example of circularity;
(c) it is available quite everywhere, from different organic materials (sludge from waste water treatment, agricultural wastes, etc.).

In case the biogas is used for the production of energy (mostly, electricity and heat in cogeneration mode), several technologies are available, from internal combustion engines to gas turbines. But a new technology is now available in the energy domain, a technology that is not a thermal engine but an electrochemical engine: the solid oxide fuel cells (SOFC); they represent by far the best technological option to convert the chemical energy of biogas in electrical energy (+ heat), reaching electrical efficiencies of around 60% independently of the size.
The project has analyzed this very new combination: biogas-fed SOFC to maximize power production using a sustainable fuel. The technological, economic and social implications, and opportunities, are high: sustainable fuel, distributed fuel, waste-to-energy, circular economy, best technologies in the market.
The analysis of a new concept has been completed: from very technical aspects to economic analysis and to social considerations. The results have been very encouraging about a possible future role of biogas in the energy domain.

Team description by skill

Francesco Enni, an Energy Engineering student from Politecnico of Milan: the *guru* of Solid Oxide Fuel Cells, he provided the team with the most accurate information about the technology at the very foundation of the whole project.

Matteo Calò, a Mechanical Engineering student from Politecnico of Turin: with his diagonal knowledge about mechanics and thermodynamics he provided the estimations needed to understand the technical feasibility of the solution.

Matteo Raviola, a Mathematical Engineering student from Politecnico of Turin: his mathematical competence was extremely useful in understanding and predict the economic and social implications of the project.

Nidhin T. Madhu, a Materials & Nanotechnology Engineering student from Politecnico of Milan: a fundamental brick of the team, he continuously provided the chemical knowledge needed to carry on the project in the most critical steps.

Rebecca del Vecchio, a Building Engineering & Architecture student from Politecnico of Milan: unsaid most worthy team leader, with her horizontal skills she provided the team with the needed regulatory context and with the most impactful graphical content.

Sandro Zarcone, a Management Engineering student from Politecnico of Milan: main and most deserving unelected speaker of the team, he alone was able to develop the most accurate business case, and much more.

«*He is The man*» (Nidhin)

Goal

During the past decade the concern for the environmental impact of electricity has become widespread: gradually, the common conscience has acknowledged the importance of the reduction of CO2 emissions and of the deployment of clean energy technologies. This has persuaded governments to generate new policies which reinterpret negative externalities and to work in unison towards a better,

greener society. A crucial step in this effort is the abatement in greenhouse gas (GHG) emissions objective. In the paper industry in particular, a lot of waste is generated every year during the production process. The question then is if that waste could instead get a second life via a transformation into useful green energy. The goal of the S2E project is to work with Fedrigoni Group, leader in the paper production industry, to answer this question. Fedrigoni needs a solution capable of producing valuable energy starting from the sludge stream, a by-product of the production process, within the very next years. This serves the double purpose of recovering energy, otherwise wasted, and reducing environmental impact targeting the carbon emissions which, given the commitment of the EU to drastically reduce them by 2030, represent a source of great uncertainty. This will enable Fedrigoni to obtain the same final industrial result while reducing the carbon footprint. Indeed, year 2030 is close and so is the targeted end date for the Sustainable Development Agenda started in 2015. The S2E project will serve as a pioneer for the introduction of a circular approach in the industrial field, where many production patterns are far from their true sustainability potential: Fedrigoni's effort to reduce the impact towards the environment shall become a reference model.

Furthermore, one of the fundamental pieces of the project is the device which should perform the last step in the conversion of biogas into energy. This must be a Solid Oxyde Fuel Cell (SOFC), an electrochemical system which exploits biogas to produce electrical and thermal energy. This is a technology in its early stages of development, hence the S2E project aims to illustrate the technical and economical practicability of SOFC systems operated at a paper production plant, effectively contributing to its spread.

Understanding the problem

This research aims at understanding if the organic sludge can be recycled in order to extract energy from it in a sustainable way. For the purpose, the following specific research questions were defined:

1) Does the paper industry sludge have an actual residual energetic potential to justify such research?
2) How should a solution be technically designed in order to perform a transformation process from organic solid matter to useful electrical energy with competitive efficiency?
3) Is the concept technically, economically and socially feasible?

These are fundamental yet nontrivial questions. The first stems from the fact that paper mill sludge is a very unusual type of biomass which has been studied very little. Efficient utilization of waste, however, is an important step towards circular economy and reduction of greenhouse gas emissions, hence the need to push the boundaries and extend the common practice of biogas extraction to more uncommon species biomass. The problem S2E aims to solve, then, is not merely sizing a plant, but it is also to shed light on the amenability of this kind of biomass to biological digestion processes. The second question regards the design of the S2E solution which constitutes the technical heart of the project. What makes this a highly nontrivial issue is the fact that there are multiple constraints. The main ones concern the input, namely the paper mill sludge, and the specific device which should perform the biogas-to-energy stage. The latter, indeed, was prescribed to be a SOFC. This on one hand comes with several advantages, such as very high efficiency and carbon neutrality, however the fact that this technology has not yet reached maturity makes its employment a risk. Then, one of the many tasks of the S2E team is to make sure that such risk is properly controlled so that

the industrial partner Fedrigoni Group can take on the project safely. Finally, the last question aims at justifying the project as a whole. The technical hurdles stem from the harmonization of an anaerobic digestion plant, which should convert the sludge into biogas, with the SOFC which takes the biogas as an input. The economical ones arise, on one hand, as a result of the possibility of low energy potential of the paper mill sludge, and on the other because of the employment of a technology at its early stages of development, i.e. the SOFC.

Sample of paper mills sludge. Source: «Characterization and Feasibility Assessment of Recycled Paper Mill Sludges for Land Application in Relation to the Environment" (R. Abdullah et al.)

Convion C60, the most suitable SOFC industrial module to integrate in the S2E solution.

Exploring the opportunities

No direct transformation from sludge to energy, such as incineration, is technologically sustainable: the sludge must be converted into biogas, and a "gas-to-energy" technology is needed for the energetic valorisation of the biogas. The intrinsic characteristic of the sludge limits the available pool of options: chemical analysis ultimately suggested the exploitation of anaerobic digestion technology, which can treat waste through a digestion process led by bacteria. On the other side, multiple solutions are available for the "gas-to-energy" side. The energy plants currently running in Fedrigoni convert a natural gas stream, coming from the national grid, into electricity and steam through a gas combined cycle: electricity, sold in the national grid provides a revenue stream; steam is essential for papermill manufactural operations. This exiting architecture is key to the realisation of the final product; nevertheless, the carbon intensity of the plant is non-negligible and the overall system efficiency is improvable. SOFC technology is, hence, chosen for the electricity generation, due to its peculiarities: higher efficiency, lower emissions and modularity. Electricity produced could be partly exploited internally for steam generation; however, the quantity of available sludge is not sufficient to fully substitute the actual architecture. For this reason, future Fedrigoni energy plants would present two separate architectures: the actual one, necessary for papermill manufactural activities, and S2E plant, for renewable electricity generation.

Generating a solution

The S2E final solution is composed by two sequential systems: an anaerobic digestor, able to collect papermill sludge producing biogas, and four Solid Oxide Fuel Cells (SOFCs), able to produce electricity while fed with the produced biogas. The pilot plant, to be located in Fabriano, is estimated to produce 228 kW of electricity, with high sludge-to-electricity efficiency. Through energy valorisation, the project can give a second life to papermill sludge, reducing at the same time by 10% the mass destined to landfilling.

Starting from a biogenic source, the project benefits from incentives coming from the Italian regulation DM FER about renewable energy sources; accordingly, the sale of the produced green energy to the grid accounts as a key economical revenue stream. Together with the avoided costs deriving from a reduction in the amount of waste destined to landfilling, these revenue streams guarantee the economical sustainability of the project. Tecno-economic analysis estimated a payback time of 10 years, over a plant lifetime of 20 years.

Nevertheless, the project generates positive externalities captured by the different stakeholders involved, such as SOFC suppliers, governments, and local companies. A net marginal social economic value (MSEV) is returned to society thanks to the green and renewable nature of the project, able to reduce landfilling and plant carbon footprint; extra value to labour market is also guaranteed for installation and maintenance of the plant.

Main bibliographic references

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