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# Hydrogen and Methane Production by Single- and Two-Stage Anaerobic Digestion of Second Cheese Whey: Economic Performances and GHG Emissions Evaluation

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**Abstract:** This study aimed at evaluating the economic performances of and carbon footprint associated with innovative systems for the energetic valorization of second cheese whey (SCW), a by-product of whey cheese manufacture, through anaerobic digestion processes. Three systems were modeled: a conventional single-stage anaerobic digester (FAD), located at about 50 km from the dairy factory; an on-site conventional single-stage anaerobic digester (CAD), located at the dairy industry; and an on-site two-stage anaerobic digester (TAD). The TAD technology enables the simultaneous production of hydrogen and methane on site. The biogases produced were combusted in combined heat and power plants (CHP), but only the onsite systems provided process heat to the dairy factory. In the specific conditions assumed, TAD configuration exhibited a higher energy output, which led to a GHG emission reduction of about 60% compared to FAD, mostly thanks to the additional hydrogen ($H_2$) production and the improved engine performances. A detailed cost analysis confirmed the results of the environmental analysis, pointing to the TAD solution as the most economically viable, with a payback period of 9 years, while the CAD had a payback time of 12 years. The results here presented aim at providing the dairy industry with a robust economic analysis on the opportunity of building an innovative system for SCW valorization, as well as providing policymakers with environmental reliable data to support the promotion of this technology.

**Keywords:** second cheese whey; anaerobic digestion; hythane; hydrogen; GHG emissions



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## 1. Introduction

Anaerobic digestion (AD) is a biological process widely applied at an industrial scale for the treatment of the organic feedstocks and wastes, with the aim of mitigating GHG emissions, recycling nutrients, and producing bioenergy (in the form of biogas) [1]. Biogas can be used for heat production by combined heat and power (CHP); can be upgraded to biomethane to be injected into the natural gas network; or can be used in the transport sector, which is expected to be its main future perspective. In 2020, there were 2159 biogas plants in Italy which generated 7.5 TWh of power (2.5% of the renewable energy produced).

Italian cheese production represents an important agro-food sector, with a total production of 1.34 Mt of cheese in 2020 [2], and it is strongly characterized by a number of small-to-medium enterprises. Istat, the Italian national institute of statistics, reports a total of 1129 dairy farms in Italy in 2020, of which 785 are considered local SME companies, working less than 5000 t of milk per year. According to ISTAT statistics [2] and CLAL (the Italian Dairy Economic Consulting agency) [3], 10.3 Mt of cheese whey was produced in Italy in 2019. Cheese whey is characterized by high concentrations of biological oxygen demand (BOD) and chemical oxygen demand (COD), with a content of around 50% of milk solids [4]. This solid matter is mostly constituted of lactose and lactalbumin, and it is partially valorized by producing whey cheeses, such as the ricotta in Italy [5]. About 50% of cheese whey is not processed or valorized as it is directly delivered to wastewater treatment plants. The ricotta production, on the basis of the precipitation of proteins by means of heat (85–90 °C) and organic acids, generates a relevant load (0.85 Mt) of waste stream, named second cheese whey (SCW) [6]. Similar to cheese whey, the SCW is characterized by high organic content (BOD: 50–60 g/L; COD: 60–80 g/L; lactose: 40–50 g/L) but contains a lower load of proteins and lipids and a higher salinity (7–23 mS/cm). Although SCW may find application in the food industry as animal feed, only a minor portion of SCW is used, and its high salinity poses a severe disposal and pollution issues for the dairy industry [7].

Nowadays, the dairy industry is commonly disposing massive quantities of SCW at off-site conventional anaerobic digestion plants operated by third parties and is mostly running on manure, energy crops, and other substrates. The alternative treatment of SCW relies on the aerobic treatment by means of conventional activated sludge processes that, however, are significantly expensive (i.e., around EUR 0.50/kg COD) [8]. Currently, there is a lack of studies dealing with SCW and its possible valorization pathways, mostly pointing to SCW as a potential source for lactose [9–11], bio-ethanol production [8,11], or fermented drinks [12].

AD could represent a valuable and profitable approach for the valorization of SCW for energy production purposes, especially in areas with a lack of animal farms nearby [4].

The AD process is catalyzed by a wide range of microorganisms acting synergistically in the absence of oxygen. The main advantages of the industrial AD process are the production of a versatile energy carrier, biomethane, and the high degree of organic matter reduction [13]. The AD process generally includes four consecutive steps, namely, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The first three steps are operated by bacteria belonging to the dominium of Eubacteria: during the hydrolysis, organic polymers are hydrolyzed by bacteria and extracellular enzymes into soluble oligomers and monomers, which are subsequently utilized to produce different amounts of volatile fatty acids, alcohols, and sugar, as well as releasing a biogas containing hydrogen ($H_2$) and carbon dioxide ($CO_2$) during the acidogenesis. The products of the acidogenic phase are then metabolized in the subsequent phases of acetogenesis with the production of acetic acid and $CO_2$. Finally, the fourth step, is operated by methanogenic archaea: from the acetic acid, $H_2$, and $CO_2$, produced during the acidogenic and acetogenic phases, the biogas, a mixture of $CH_4$ and $CO_2$, is produced.

The whole AD process is driven by the ability of microorganisms to cooperate to degrade raw materials from complex to simple products. Monitoring and control of the involved factors—substrate (quantity and quality composition), temperature, pH, organic matter content, design of the bioreactor, and microbial community dynamics and interactions—play an essential role in process optimization in order to obtain the maximum benefit from this technology, both in terms of energy production and biological stability of the digestate [14].

Due to the high easily fermentable organic content and low bicarbonate alkalinity of the raw SCW, the acidogenesis phase of the AD undergoes fast acidification with a lowering of the pH, which results in being far below the optimum value for the growth of methanogen archaea [15]. In order to control acidification and rule out the risk of a failure for the anaerobic process, an increase in alkalinity or an appropriate dilution are required. A possible solution is the use of two-phase configuration, which, besides allowing a combined production of $H_2$ and $CH_4$, offers an alternative solution in terms of process efficiency and stability [16,17]. This approach is based on the concept that the acidification phase and the methanogenic phase are performed in two separate reactors, allowing the two different bacterial guilds to operate in their specific optimal conditions of pH and growth rate.

The two-phase process configuration was studied for the first time in 1971 by Pohland and Ghosh [18], and in recent years was further developed, demonstrating that higher methane yields could be obtained by two-stage configurations with simultaneous production of hydrogen [19]. In addition, a mixture of hydrogen (10–25% by volume) and methane, called Hythane, is considered an advanced and transitional biofuel that has many advantages as it improves the efficiency of methane combustion and decreases $CO_2$ and CO emissions [20,21]. There are no studies in the literature evaluating the potential impact of the applications of the two-phase anaerobic digestion of SCW to co-produce hydrogen and methane. The scope of this work is to fill this gap by evaluating the economic and environmental performances of the two-phase anaerobic digestion of SCW.

To this aim, the present work reports the case study of a dairy factory dedicated to "ricotta" cheese production, located northeast of Rome, which, with 3500 t of milk processed annually, effectively represents the Italian dairy small–medium enterprises. For this reason, the scenario presented in this study can be considered representative of a significant market segment.

Economic and LCA (life cycle assessment) analyses were performed with the aim of providing a scientifically sound comparison of different types of SCW valorization for the production of renewable energy in form of methane and hydrogen. Three systems were modeled: the reference scenario, an off-site anaerobic digestion plant (FAD) where currently the SCW is transported and disposed of; an on-site conventional single stage anaerobic digester (CAD); and an on-site two-stage anaerobic digester (TAD) for hydrogen and biogas production. The two alternative processes proposed were previously optimized and set up at a laboratory scale [22].

The aim of this work was to provide the dairy industry with a robust economic analysis on the opportunity of building an innovative system for SCW valorization, as well as to provide stakeholders and policymakers with reliable data on the GHG emissions of the systems analyzed to support the promotion of efficient solutions in order to mitigate the climate impacts of this industrial sector.

## 2. Materials and Methods

To assess the economic and environmental performances of the adoption of the two-stage anaerobic digestion for the energetic valorization of SCW, the FAD, CAD, and TAD systems were characterized, and detailed mass and energy balances were elaborated in order to enable an accurate and credible economic and environmental assessment. The environmental assessment was carried out with a life cycle thinking approach, here limited to GHG emissions, as GHG emissions reduction is the main environmental purpose and outcome of the two-stage anaerobic digestion adoption. Conversely, the economic performances assessment is based on the calculation of a set of economic viability indicators commonly used for project investment assessment: the net present value (NPV), the payback period (PBP), and the internal rate of return (IRR), which were considered in this study.

### *2.1. System Description*

The three different AD process settings for SCW treatment evaluated in this case study are

- FAD: Off-site anaerobic digestion. It represents the current situation of the dairy factory under analysis. The SCW produced is delivered to a third-party AD plant located off-site, approximately 50 km away from the production facilities. Transportation costs are covered by the dairy factory, while SCW is supplied free of charge to the AD plant. In this system, the real costs incurred by the dairy to dispose of SCW and wastewater are considered.
- CAD. Conventional mono-stage anaerobic digestion. The SCW is disposed of by the company itself. The dairy factory is equipped with its own conventional mono-stage anaerobic digestion plant installed on site, able to treat the entire volume of SCW produced by its ricotta production facility, with the aim at both disposing of SCW and generating power and heat by means of a CHP (combined heat and power unit). The dairy factory is conceived to be equipped with an aerobic wastewater

treatment system for the disposal of the digestate produced and of the washing water (wastewater) derived from the cleaning up of the entire production cycles (e.g., tanks, silos, and lines).

- TAD: Two-stage anaerobic digestion. A two-stage anaerobic digestion plant is installed on site to increase the efficiency of biogas production by separating the acidification phase and the methanogenic phase. The system produces both hydrogen and methane. In TAD, the company is equipped with the same wastewater treatment and CHP units considered in CAD.

Costs and yields of biogas, hydrogen, and methane were estimated assuming the optimized process configurations of the experimental pilot plants presented by Lembo et al. [22]. Optimization studies of the different process cycles were in fact previously performed at the ENEA Casaccia laboratories, wherein experiments specifically focused on highly efficient biogas production via AD processing of SCW were carried out. The experimental set-up was fine-tuned as follows: the mono-phase reactor in CAD mode was characterized by 51 L working volume, 7.5 days of hydraulic retention time (HRT), fed at an organic loading rate (OLR) of 0.67 gVS (Volatile Solids)/Lr d-1. The pH control was achieved by influent dilution (1:1) with the digestate. The first phase (3.4 L working volume) of the bi-phase reactor of TAD mode was fed with SCW diluted (1:5) with phosphate buffer (0.2 M) at an OLR of 10 gVS/Lr d-1 (HRT 24 h). As the mono-phase reactor, the second phase was tested at OLR of 0.67 gVS/Lr d-1 (HRT 7.5 day). All the considered reactors are continuously stirred tank reactors continuously fed.

These operating settings were scaled-up to the real operating conditions of the case study. The dairy factory produces 9 t/day of SCW. In the CAD and TAD system, dilution factors of 1:10 and 1:5 were considered, respectively, assuming the density of 1 g/mL of the substrate. The sizes (volumes) of reactors were obtained by multiplying the daily SCW load by the HRT (Table 1). The incoming organic load (in tVS/y) was calculated by multiplying the VS content of incoming substrate by the SCW load, assuming 300 working days per year.

**Table 1.** Summary of experimental results of CAD and TAD.

| | Unit | CAD | TAD | |
|---|---|---|---|---|
| | | | First Reactor (Hydrogen) | Second Reactor (Biogas) |
| **Biogas production** | L day$^{-1}$ | 17.1 ± 0.96 | 10.2 ± 1.1 | 19.8 ± 0.60 |
| **Methane/hydrogen content** | % | 56.3 ± 0.65 | 39 ± 2 | 58.7 ± 1.2 |
| **Biogas/hydrogen flow** | L day$^{-1}$ | 9.59 ± 0.54 | 3.91 ± 0.50 | 11.6 ± 0.4 |
| **Specific production** | L gVS$^{-1}$ | 0.28 ± 0.016 | 0.12 ± 0.02 | 0.34 ± 0.13 |
| **Volume of digester** | L | 51 | 3.4 | 51 |
| **Hydraulic retention time** | Days | 7.5 | 1 | 7.5 |
| **Organic loading rate** | gVS (L$_{reactor}$ day)$^{-1}$ | 0.67 | 10 | 0.67 |

Finally, the annual hydrogen and methane production were calculated by multiplying the experimental specific gas production by the total amount of VS (tVS/y) (Table 1), whereas the total energy production was estimated by adopting the lower calorific values of 35.88 MJ/m$^3$ and 11.1 MJ/m$^3$ for $CH_4$ and $H_2$, respectively.

Electricity and thermal energy production via combustion in an internal combustion engine co-producing heat and power is calculated with a net electric efficiency of 32% for CAD [23] and 35% for TAD. The higher efficiency of TAD is set according to the work of Genovese et al. [20] as the engine running on a mixture of $CH_4$ and $H_2$ has an efficiency about 10% higher than engines running on natural gas thanks to the $H_2$ fuel properties. The heat production share was set to 40% of the energy content of the biogas and hydrogen produced.

Performances of CAD and TAD are summarized in Table 1.

### 2.2. Economic Analysis

An economic analysis was carried out for the three different systems of SCW disposal through anaerobic digestion for a dairy factory producing 9 t of SCW and 25 t of washing water daily.

The same methodological approach described in Agostini et al. [23] was adopted: the NPV, the IRR, and the PBP. These indicators of the financial performances of economic investments were used to quantify whether the project was viable, i.e., the net revenues were able to pay back the capital invested.

To calculate the NPV, the annual inflows and outflows of the project were estimated through applying the discounted cash flow approach. This approach internalized the impact of the different timings of future cash flows by applying a discount rate to calculate their current value [24,25]. The discount rate represents the possibility of generating revenues by investing the capital differently. A discount rate of 5% was used according to the recommendation of the European Commission for project appraisal [26]. The net NPV was therefore calculated as the sum of the discounted cash flows. A project is economically viable if the NPV is positive. Obviously, he higher the NPV, the more profitable and less risky the project [27]. The NPV is expressed as follows:

$$\mathrm{NPV} = -\mathrm{C}_0 + \sum\nolimits_{t=1}^{n} \frac{\mathrm{R}_t - {\mathrm{C}_t}^{\mathrm{O\&M}}}{(1+\mathrm{r})^t} \tag{1}$$

where

$C_0$ = capital expenditure;
$R_t$ = revenue in time period t;
${C_t}^{O\&M}$ = operating and maintenance costs in time period t;
R = discount rate (%);
t = time period from 0 to *n* (years).

The IRR is calculated as the discount rate at which the NPV becomes zero. It is therefore the discount rate that makes the present value of future revenues equal the present value of costs.

Hence, the IRR is defined as

$$0 = -\mathrm{C}_0 + \sum\nolimits_{t=1}^{n} \frac{\mathrm{R}_t - {\mathrm{C}_t}^{\mathrm{O\&M}}}{(1+\mathrm{IRR})^t} \tag{2}$$

where

$C_0$ = capital expenditure;
$R_t$ = revenue in time period t;
${C_t}^{O\&M}$ = operating and maintenance costs in time period t;
R = discount rate (%);
t = time period from 0 to *n* (years).

The IRR is a percentage, unlikely the NPV, and it is uncorrelated with the project size. Its use makes possible the comparison of investment projects independently of their size. The IRR is easy to interpret—if it is lower than the discount rate, it is more profitable to invest the capital in other projects, whereas if the IRR is higher than the discount rate, the project should be viable. Overall, the higher the IRR, the more secure and profitable the investment [26].

In the economic evaluation, the following assumptions were made:

1. FAD includes the present costs currently incurred by the company, relying on the SCW delivery to the off-site anaerobic digestion plant at a cost of EUR 15/t with a total

volume of 2700 t/year of SCW, taking into account 300 working days per year. No investment cost was considered, as the biogas plant is out of the system boundaries.

2. In CAD and TAD systems, the capital costs (CAPEX) for the construction of an anaerobic digestion plant (including buildings plant, machinery, etc.) and the startup cost (including design, planning authorization) are considered. The operating costs (OPEX) include labor, machinery depreciation, fuels and power, maintenance, and insurance.

The lifetime of the project was set to 20, which corresponded to the expected life of the plant and the Italian feed-in tariff duration. Decommission costs and residual were not considered as that the time horizon of the analysis and the lifetime of the plant coincided.

In order to properly estimate the investment cost, a market survey was conducted. The company CINE LTD (Italian Society New Energies) provided us with a quotation of a conventional mono-phase plant. It was scaled down according to the pilot plant characteristics and company production yields, as follows:

$$\text{Cost 2} = \text{Cost 1}\left(\frac{\text{Volume 2}}{\text{Volume 1}}\right)^{0.6} \quad (3)$$

The company asjaGen provided us with the quotation of microgenerators: the tandem type was also produced for 25 kW power. The cost of TAD was increased to 20% in order to counterbalance an expected higher complexity of the control systems.

The resulting investment costs were in agreement with the data reported in the literature. The Politecnico of Milan performed two market screenings [28] and pointed to comparable investment costs with respect to those supplied by CINE LTD. Agostini et al. [24], in a study investigating electricity production from AD of different substrates, reported investment costs being within a comparable range.

Operation, maintenance, and insurance costs were scaled for the installed capacity, with the addition of a co-generator. Professional consultancy for advice in the various process activities from experts operating in the same industrial sector were estimated at around EUR 1400/year. Mass and energy balances of the systems are reported in the LCA inventory in Section 2.3.1.

Regarding the aerobic wastewater treatment for the digestate management, both the CAPEX and the OPEX estimations were based on personal communication and quotations provided by two companies operating in the relevant industrial sector, i.e., Studio Scoccia srl and Delta acque srl.

In CAD and TAD, the installation of a digestate management system for the digestate and washing water treatment was considered, with a total volume of 120 $m^3$ per day. The revenue flows associated with CAD and TAD biogas production were calculated according to the Italian feed-in tariff system [29], i.e., the electricity annually sold to the grid (only 89% of the produced electricity can be sold and delivered to the grid, according to Italian legislation) was multiplied by the incentive rate for this type of plant and waste substrate (EUR 0.233/kWh).

The revenues from the saved NG represent the cost saved for the purchase of NG used for heating purposes within the dairy factory thanks to the heat provided by the CHP.

The Italian average gross price at the virtual exchange spot market in the first five months of 2022 was EUR 1.4794/$Sm^3$ [30]. Assuming an average PCI of 35.5 MJ/$Sm^3$, the company requires 38,353 $m^3$/y of natural gas with a cost of EUR 56,739/y. CAD and TAD, by employing the CHP, produce around 46% and 63% of the company's thermal energy requirements, respectively. Taking into account the price of natural gas, costs incurred by the dairy company in CAD and TAD systems were EUR 30,501/y and EUR 21,155/y, respectively. The savings accrued with the replacement of the natural gas heat with the heat from the SCW biogas CHP amounted to 46% and 63%, respectively for CAD and TAD, with respect to the annual expenditure for natural gas consumption dedicated to internal use.

Results of the cost contribution analysis are reported in Figures 1 and 2.

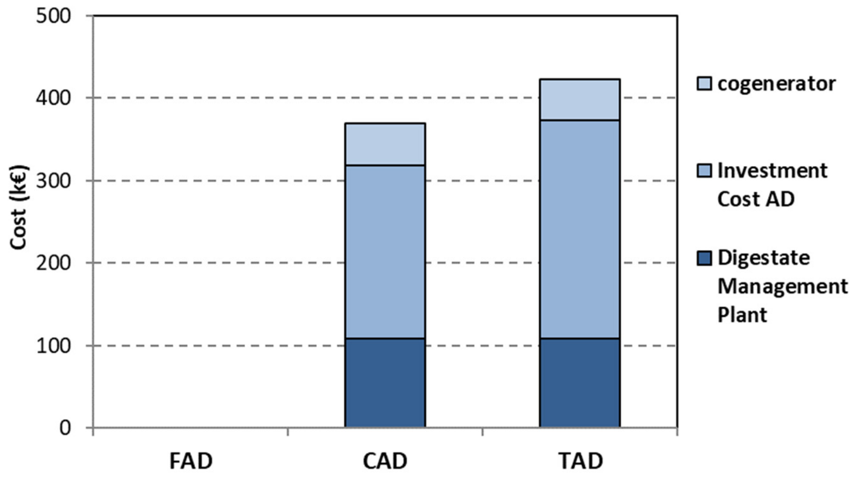


**Figure 1.** Cost contribution analysis: Capex.

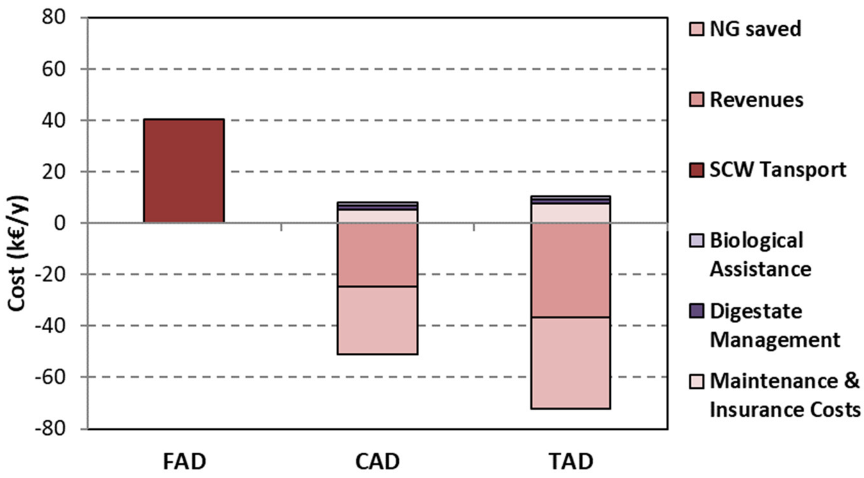


**Figure 2.** Opex expenditures: annual cost contribution analysis.

### *2.3. Life Cycle Assessment*

An environmental life cycle assessment (LCA) was performed according to the ISO 14040/14044 standards [31,32] (European Commission) recommendations [33], and therefore was structured in four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. Goal and scope and the life cycle inventory are presented in this section, and the life cycle impact assessment and the interpretation phases are reported in the Results and Discussion section.

#### 2.3.1. Goal and Scope

The main scope of this analysis was to evaluate the environmental performance in terms of carbon footprint associated with the disposal of SCW by carrying out an attributional comparative analysis. The three alternative systems, namely, FAD, CAD, and TAD, were compared in a lifetime of 20 years. The disposal of the quantity of SCW produced in one year was identified as the functional unit for this study. To allow for an improved understanding of the parameters most impacting in terms of carbon footprint, the systems were split into four sub-systems:

- SCW transport (only for FAD);
- Anaerobic digestion;
- Energy production by CHP;
- Digestate management plant.

In FAD, we assumed that all the produced SCW was delivered to the off-site AD plant, and there it was properly treated via AD processing; conversely, yields of methane, credits for the electricity produced, and emissions related to the processes involved were the same as CAD. The blue dashed lines in Figure 3 (FAD reference scenario) and Figure 4 (CAD and TAD, the two alternative systems considered in the present case study) show the system boundaries of the three options. In FAD, the foreground system consisted of the SCW transport and part of the off-site biogas as the CHP and digester structures were also used for the digestion of other substrates, while in CAD and TAD, the anaerobic digester and the CHP were fully dedicated to SCW processing. (Figure 3).

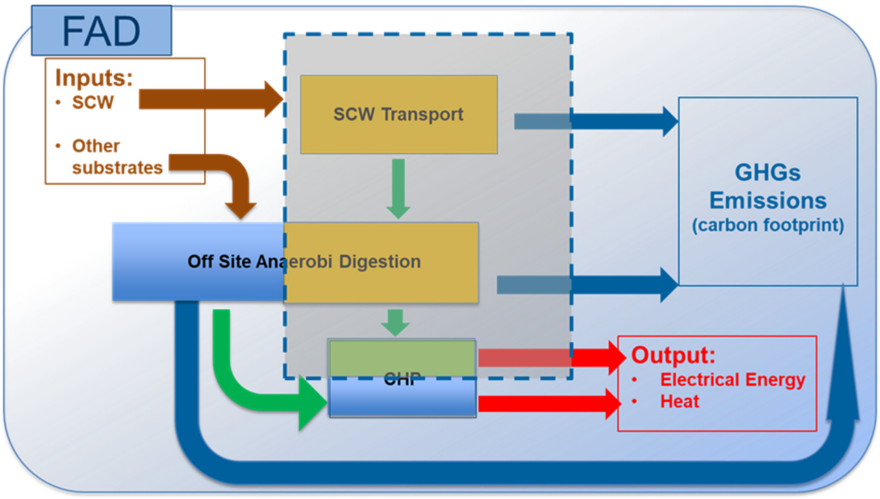


**Figure 3.** System boundaries of the reference scenario (system 1, FAD).

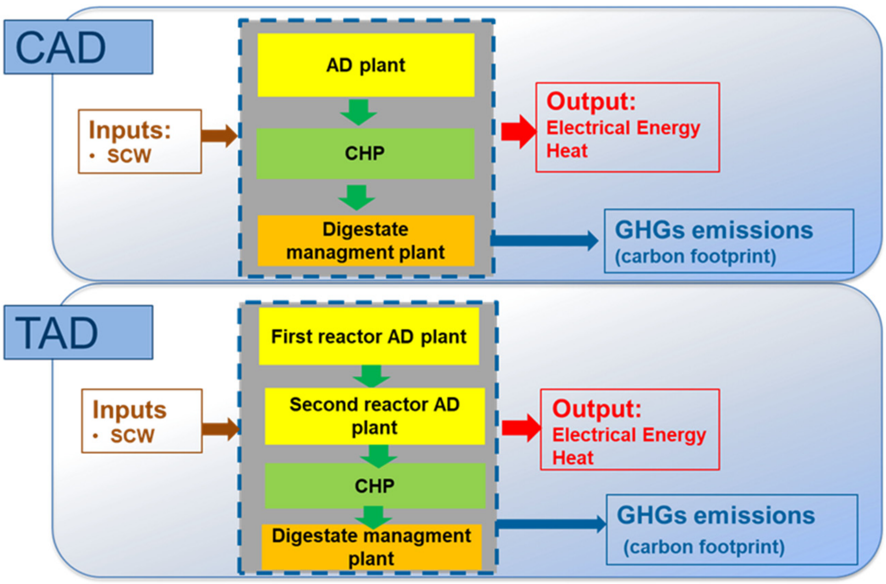


**Figure 4.** System boundaries of the CAD and TAD systems.

### 2.3.2. Life Cycle Inventory

The life cycle inventory analysis involved a systematic inventory of the input and output of energy and material flows during the entire life cycle and was compiled by coupling data obtained from the experimental results (as mentioned above in Section 2.1) with data from a potential real plant and with the most similar process datasets available in the commercially available background database ecoinvent for the materials and technologies deployed. Table 2 reports the main mass and energy flows considered in the three systems analyzed. As the excess power was exported, in order to internalize the reduced GHG emissions achieved by replacing other sources of power in the Italian power grid, the specific GHG emissions of the Italian power mix from ecoinvent were considered to be avoided. The heat produced by the CAD/TAD CHP plant was assumed to replace heat generated by a natural gas boiler, and it was taken from ecoinvent with the Italian natural gas mix as input. The feedstock, SCW, was considered a residue, and no emissions were allocated to it. The infrastructure considered was the ecoinvent agricultural biogas plant, downsized linearly to the size of the plants considered. For the CHP, an efficiency of 32% was assumed if running on biogas, and 35% if running on a mixture of biogas and hydrogen thanks to the improved ICE performances (about 10% according to Genovese et al. [20]), with an internal consumption of 11% of the power produced and 8000 h at full capacity per year. A methane slippage of 1.7% was considered, according to Liebetrau et al. [34]. The emissions from tap water provision and wastewater treatment were taken from ecoinvent as well.

**Table 2.** Mass and energy flows related to the three systems.

| | Unit | FAD | CAD | TAD |
|---|---|---|---|---|
| **Daily milk processed** | t day$^{-1}$ | 11.5–12 | 11.5–12 | 11.5–12 |
| **Daily whey production** | t day$^{-1}$ | 10 | 10 | 10 |
| **Daily SCW production** | t day$^{-1}$ | 9 | 9 | 9 |
| **CHP installed capacity** | kW | 0 | 15 | 22 |
| **CHP efficiency** | % | 32 | 32 | 35 |
| **Thermal efficiency** | % | 0 | 40 | 40 |
| **Power produced** | MWh | 119 | 119 | 176 |
| **Annual thermal needs (milk 4°–35°, whey 35°–90°)** | GJ year$^{-1}$ | 1157 | 1157 | 1157 |
| **Heat from CHP** | GJ year$^{-1}$ | 0 | 535 | 726 |

A fundamental aspect for the environmental (and also economic) performance of biogas plants is represented by the valorization of the heat recovered by a CHP at the dairy factory. The studied dairy factory processes about 12 t/day of milk, which generates 10 t/day of CW and a final production of 9 t/day of SCW. An energy of 1.26 MJ/y is needed to heat such volumes of materials from +4 °C, temperature, at which the milk is kept at the dairy factory, to +35 °C for cheese production and to +90 °C for ricotta cheese production. To this purpose, a methane-powered boiler is used in the reference system.

The materials and energy flows identified in the life cycle inventory phase were categorized and assigned to the relevant impact category using the software GaBi [35]. The evaluation was at mid-point (i.e., the emissions to the environment were quantified, not the impact at the end point). The assessment method adopted was the recommended methods for global warming by the International Panel on Climate Change Assessment Report 5; the metric used to measure climate change was Global Warming Potential with a 100 years' timeframe (GWP100).

## 3. Results and Discussion

### *3.1. Economic Assessment*

The financial NPVs for FAD, CAD, and TAD are shown in Figure 5. They were estimated by applying a discount rate of 5%. Investment cost and profitability criteria for CAD and TAD are shown in Table 3.

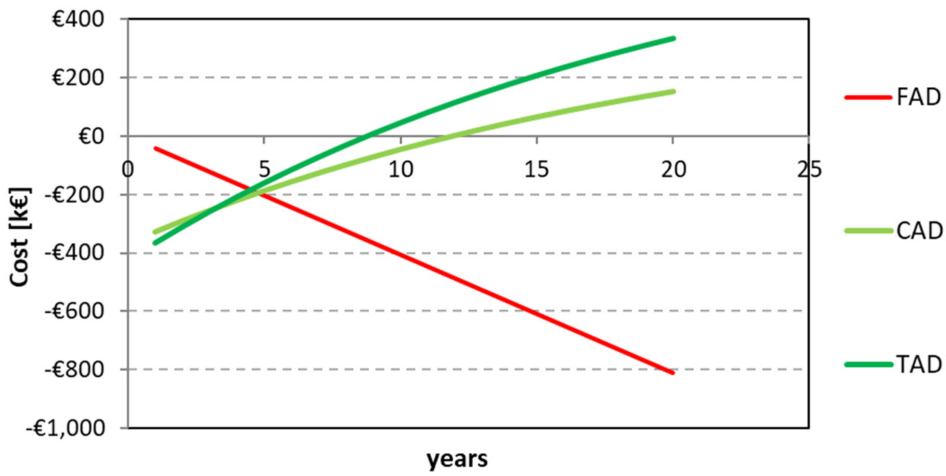


**Figure 5.** Net present value for the three systems.

**Table 3.** Investment costs and profitability criteria.

| | Unit | CAD | TAD |
|---|---|---|---|
| **Capex** | k€ | 370 | 429 |
| **Opex (including natural gas savings)** | k€ $y^{-1}$ | 2.96 | 0.998 |
| **Total energy production** | GJ $y^{-1}$ | 1338 | 1815 |
| **Power production** | MWh $y^{-1}$ | 119 | 176 |
| **Revenues (power sold)** | k€ $y^{-1}$ | 25 | 36 |
| **Thermal energy produced** | GJ $y^{-1}$ | 525 | 726 |
| **Natural gas savings** | k€ $y^{-1}$ | 6 | 10 |
| **Installed capacity** | kW | 15 | 22 |
| **Net present value** | k€ | 155 | 334 |
| **Payback time** | years | 12 | 9 |
| **Internal rate of return** | % | 9.6 | 13.2 |

FAD reflects the current economic output, with no investment cost and no revenues from SCW management. It accounts for an outflow of 15 €/t of SCW, with a total volume of 2700 t/year, corresponding to a total cost of 40.5 k€/y for SCW delivery to the AD plant. Cost due to washing water management corresponded to 2.5 k€/y, leading to a total cost, in the time frame of 20 years, of about 810 k€. On the contrary, CAD and TAD presented high-investment costs of around 370 k€ and 423 k€, respectively, but, at the same time, they counted a return associated with both the sale of electricity to the grid and the use of heat from CHP for company use. CAD showed a positive NPV of +155 k€, while TAD had a positive NPV of +334 k€, much greater than CAD. The IRR confirmed the results. The TAD system showed a higher IRR of 13.2% versus an IRR of 9.6% of CAD, with respect to the discount rate of 5%, suggesting that both systems are economically viable but that the TAD system might be more economically profitable and less risky. The TAD payback time resulted in 9 years versus the 12 years of CAD. The PBP was similar to that found by [24], who found that with the same economic analysis applied to energy crops and manure, only biogas plants running on manure had a positive NPV, and their PBP was about 6 years. The better economic performance of TAD can be explained by the fact that it produces more electricity than CAD (176 MWh/y against 119 MWh/y, respectively), due not only to a greater production of methane but also to the simultaneous production of $H_2$. Indeed, $H_2$ contained in biogas produced by TAD determined an increase in thermal energy and the improvement of the internal combustion efficiency of the CHP by raising the electrical output by 10% with respect to the same CHP powered by $H_2$-free biogas [36].

Furthermore, the better economic profitability of the TAD system compared to the FAD system was given by a greater production of thermal energy, which translated into a lower consumption of methane for the dairy factory heat internal uses. The methane consumption saving corresponded to 17,700 $m^3$/y and 24,000 $m^3$/y for CAD and TAD, respectively, with respect to the FAD system.

The financial indicators show that the investment was profitable for both CAD and TAD; moreover, it should be noted that the current adopted system (i.e., FAD) has enormous costs for the company that, over the time horizon of 20 years considered in this study, would lead to an economic loss of about 810 k€ to be dedicated to SCW management. By adopting CAD and TAD, the corresponding savings resulted in being 36 k€/y and 61 k€/y, respectively, if calculated with respect to FAD, which can be ascribed to avoided transportation costs, revenues from electricity sold to the grid, and usage of thermal energy for internal uses.

Economic Sensitivity Analysis

Capital costs of biogas plants are highly variable. There is a multitude of technologies that can be potentially employed in biogas plants. The economic margin of biogas projects may be strongly impacted by this parameter. The impact of the capital cost of a biogas plant on its economic performance is shown in the first two columns of Figure 6. The error bars correspond to the ±10% range of CAPEX.

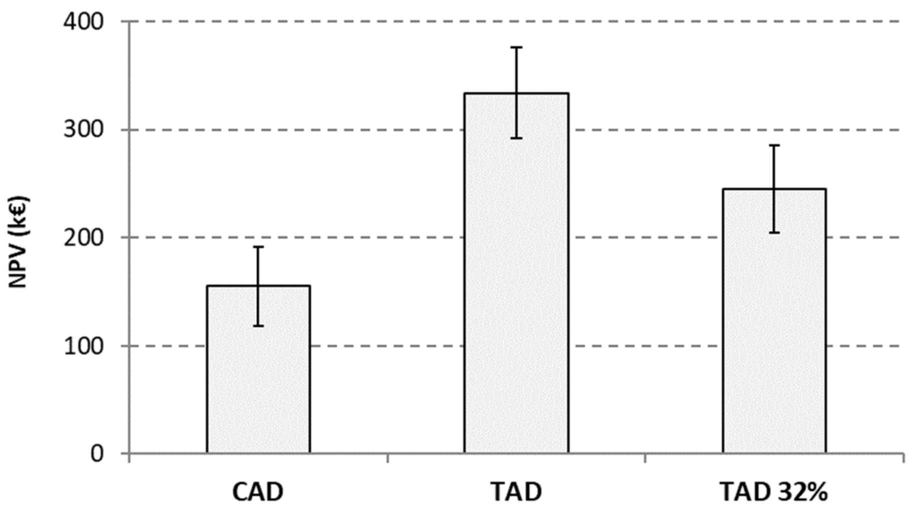


**Figure 6.** Sensitivity analysis: the error bars correspond to the ±10% range of CAPEX.

A variation of the CAPEX of around ±10% affects the NPV considerably. In the CAD system, it led to a variation of about 50% in the NPV, while in the TAD system, the variation of NPV reached about 25%. This difference was mainly due to the lower profitability of the CAD investment. These results point to the initial cost as a critical barrier for this type of investment. Thus, in such small plants for dairy SMEs, the initial investment cost must be considered a key factor for the evaluation of the entire investment.

Since the sale of electricity provides significant revenues for biogas, together with the natural gas displaced by the heat produced, CHP performance also plays an important role in the profitability of financial investments. Therefore, in addition to the TAD and CAD system, as shown in Figure 6, a column representing the TAD 32% indicated the NPV of the TAD system with a CHP electrical efficiency that did not take into account the additional efficiency provided by $H_2$ combustion (i.e., 32%).

The sensitivity analysis was performed by assuming TAD's electrical efficiency of 32% CHP, i.e., without improving efficiency due to $H_2$ combustion. Even in this case, the economic performances were highly affected, with a decrease in the NPV of about 35%.

An additional aspect that significantly impacted the economics of the modelled systems was the cost of the natural gas saved.

In recent months, gas prices have reached unprecedented levels. The natural gas average gross price from January to August in 2022 was EUR 1.8978/$Sm^3$, an increase of about 30% compared to the price considered in this study. Moreover, in August 2022, the natural gas gross price was EUR 2.499/$Sm^3$, an increase of about 70% compared to the price considered in this study.

In this global scenario, the use of waste heat from the CHP unit for internal use by the company made the investment for CAD and TAD systems extremely profitable for the company.

*3.2. Carbon Footprint*

Figure 7 shows the results of the carbon footprint calculations, also detailing the contributions of the single processes. In the FAD scenario, emissions associated with the SCW transport were essentially balanced out by the credits due to renewable power generated in the off-site plant. In CAD and TAD systems, thanks to the avoidance of the SCW transport, but especially thanks to the avoidance of GHG emissions related to the grid power production replaced and the use of natural gas avoided, the emissions savings were of an order of magnitude higher. Indeed, as shown in Table 4, the total GHG emissions savings resulted in −7.4 $tCO_2$, −76.3 $tCO_2$ eq, and −123.6 $tCO_2$ eq, respectively, for FAD, CAD, and TAD.

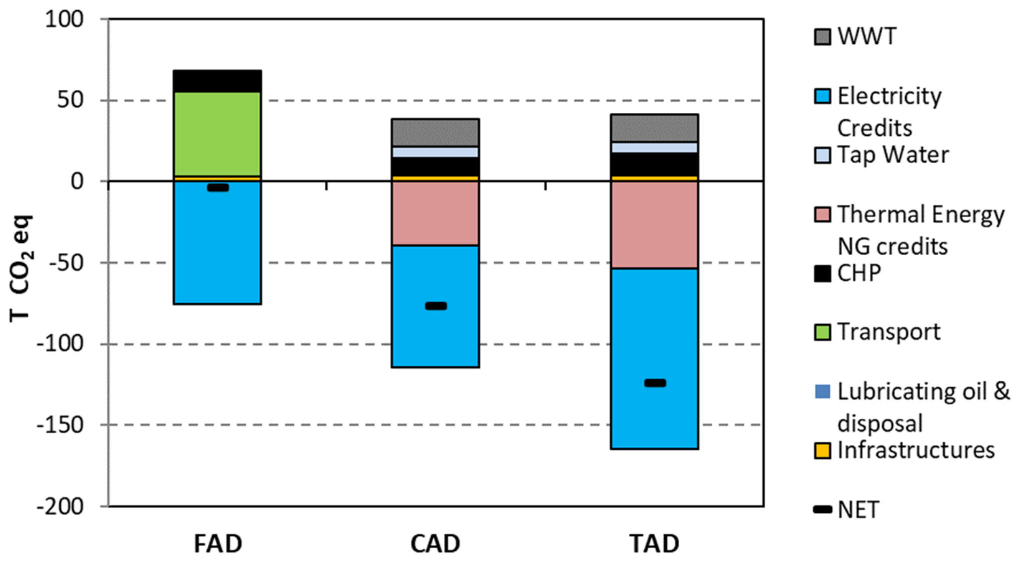


**Figure 7.** Process contribution analysis of the total $CO_2$ eq emissions.

**Table 4.** GHG emissions of the three systems (t of $CO_2$ equivalent in 20 years).

| | FAD | CAD | TAD |
|---|---|---|---|
| Process emissions | 68.0 | 38.3 | 41.2 |
| Thermal energy natural gas credits | 0 | −39.2 | −53.2 |
| Electricity credits | −75.4 | −75.4 | −111.6 |
| Total | −7.4 | −76.3 | −123.6 |

Thus, the avoidance of SCW transport and the GHG emission credits gained by replacing natural gas heat combustion for satisfying the dairy factory thermal needs and electricity from the power grid with the power produced by the CHP represent an opportunity for dairy companies and make CAD and TAD systems two valuable solutions in terms of GHG emissions mitigation. In particular, the latter, the two-stage process configuration, thanks to the additional production of hydrogen, which enables a greater output of electricity and heat, leads to a much higher potential of GHG emissions avoidance, of about two-thirds (62%) with respect to the conventional mono-stage configuration on-site and more than 15-fold the GHG savings of off-site conventional disposal of SCW.

## 4. Conclusions

The present study represents an unexplored proof-of-value investigation assessing the potential economic and environmental benefits associated with biogas and hydrogen production via anaerobic digestion of second cheese whey.

Results of the economic analysis pointed to the on-site treatments (i.e., CAD and TAD) of SCW as economically profitable for the company thanks to the electricity produced and sold to the grid, and also thanks to the thermal energy used by the company to replace the methane purchased to heat the milk and the whey.

The results, with respect to all three economic indicators used, show that TAD had a better profitability than CAD. This different behavior between CAD and TAD can be explained by higher energy yields, essentially due to higher energy production thanks to the simultaneous production of hydrogen. Indeed, hydrogen represents an added value as it increases both the energy electricity production and CHP efficiency.

Regarding the carbon footprint of the systems analyzed, the avoidance of the SCW transport to the off-site AD plant, but especially the GHG emissions avoided thanks to the renewable energy production (both the thermal and electrical energy generated by the CHP), led to the result that CAD and TAD showed greater GHG emissions savings with respect to the current FAD system (which saved about $-7.4$ t$CO_2$ eq) of about 10- and 15-fold ($-76.3$ t$CO_2$ eq and $-123.6$ t$CO_2$), respectively.

The disposal of untreated dairy wastewater remains a major problem for the dairy industry, which demands simple and economical solutions. AD implementation at the dairy level could provide most of the electricity and heat necessary for the plant, improving the energy balance reducing transport and management costs, as well as the environmental impacts.

A limitation of the study lies in the volatility of energy markets, and therefore the economic analysis may need to be revised in future energy market contexts. However, we have shown, with a sensitivity analysis, that even though the economic performances are heavily affected by changes in the CHP performances, the NPV of the project would still result in being positive. We conclude that due to high investment cost, a stable legislative framework and incentivizing policies are required to encourage small and medium dairy enterprises in the implementation of alternative methods for SCW disposal such as those presented in this work to both enhance their economic competitiveness and generate environmental benefits.

Further work may be needed in confirming the results obtained on a larger scale, involving a demo plant, in order to bring the technology closer to the market.

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## Abbreviations

AD: anaerobic digestion
BOD: biologic oxygen demand
CAD: conventional anaerobic digester
CHP: combined heat and power engine
COD: chemical oxygen demand
FAD: off Site anaerobic digestion
GHG: greenhouse gases
ICE: internal combustion engine
IRR: internal rate of return
LCA: life cycle assessment
NG: natural gas
NPV: net present value
PBP: payback period
SCW: second cheese whey
TAD: two-phase anaerobic digestion
VS: volatile solids

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