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# Sustainable Milk Powder Production using Enhanced Process Integration and 100 % Renewable Energy

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This paper presents a Total Site analysis of the requirements to integrate 100 % renewable energy into a 10 t/h ultra-low energy milk power factory of the future in New Zealand and California. The location of the factory is important for selecting renewable energy options and therefore three case studies from three different locations are reported. In New Zealand the best option is to use renewable electricity from wind, hydro and geothermal for the factory electrical needs, and high temperature geothermal energy when available for process heating up to 210 °C and low temperature geothermal energy with MVR technology upgrading for process heating up to 180 °C. When no geothermal energy is available the best option is renewable electricity driven heat pumps for heating up to 85 °C, and biomass (wood residue) for high temperature heating up to 210 °C. Biomass production, however, will require 35 % more land than the farms require for producing the milk. In California renewable energy is best met using biogas from anaerobic digestion of cow manure and solar thermal. Biogas converted into biomethane on farm fuels a combine cycle gas turbine with a heat recover steam generator (HRSG) to meet process heating needs above 80 °C and all factory and biogas compression electrical needs. Solar thermal with day-night storage provides hot water utility. A cow manure collection rate of 37 % is required to meet both process heat and electricity needs.

## 1. Introduction

Sustainable food production and processing is a topic of increasing global importance. Traditionally the demand for dairy products per capita has been high in Europe and North America, and low in Asia. However, with increased global connectedness and trade, the demand for dairy in China, India and the Middle East is rapidly rising. For countries that produce a lot of dairy products, like New Zealand (about 20 % of export earnings), introducing sustainable farming practices and renewable energy into the dairy processing is of increasing importance in a carbon emissions and resource constrained world.

New Zealand and California produce similar quantities of milk annually (19 billion litres). Most of the milk in California is processed as fluid milk, whereas in New Zealand milk supply far exceeds domestic demand and 75 % of the milk is dried into milk powder for export. California also produces milk powders but to a much lesser extent. In terms of renewable energy, California has a favourable supply of solar energy and a highly fertile inner valley region with irrigation supporting intensive farming and potentially biogas production from cow manure. New Zealand, on the other hand, has fertile grazing land, good rainfall, and a large supply of low temperature geothermal heat, considerable waste biomass and a high level of renewable electricity through wind, hydro and geothermal. The land, water and renewable energy resources of these regions makes possible the long-term potential of having sustainable milk powder production in these regions. Careful use of the limited resources will, however be critical, especially the energy resources.

Many food processing industries over the last century have primarily met thermal and electrical energy needs using fossil fuels. Coal, natural gas and oil have been the main fuels for this purpose. The high energy density of oil has made it economical to transport fuel over long distances and the costs of oil extraction and oil refining have been relatively low. The use of coal and natural gas has generally been more localised, but in some cases large scale shipping of coal and compressed natural gas (CNG) has also been economic. Wood processing residues for energy production has generally been restricted to the wood processing sector, but as

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fossil fuel reserves inevitably become depleted, and the pressure for extensive carbon emission reduction continues, other more sustainable energy options like geothermal, wind, hydro, solar and biomass will need to be applied to the industrial processing sector (Schnitzer et al., 2007). Clever use of process integration solutions for reaching minimum energy targets will also be an important strategy for meeting current and future energy needs of the process industry sector.

The aim of this paper is to investigate options for supplying 100 % renewable energy to and ultra-low energy milk powder plants of the future located in three different geographical regions; one in California and two in New Zealand. Three case studies are reported: (Case study 1) NZ with high availability of geothermal, (Case study 2) NZ with high availability of wood residue and renewable electricity, and (Case study 3) California with solar thermal and biogas (biomethane).

## 2. Specific energy levels in milk powder processing

The production of milk powder from raw milk is an energy intensive process that begins on the farm with milking and chilling, delivery to the factory, then milk separation, heat treatment, evaporation, spray drying, packing and storage. Utilities include steam, hot water, chilled water, electricity and compressed air. High pressure steam (HPS), medium pressure steam (MPS), high temperature hot water (HTHW) and low temperature hot water (LTHW) are all used for delivering process heating up to 210 °C. Chilled water (CHW) is used for process cooling down to 4 °C. Electricity is used for driving pumps, fans, conveyors and compressors including mechanical vapour recompression (MVR) units, and for running control systems, instruments, office equipment, lighting and building services. Milk powder plant specific energies range from 5,000 to 12,000 MJ/$t_p$ of powder for thermal and in the order of 150 to 400 $kWh_{ele}/t_p$ for electricity (Ramírez et al., 2006). On-farm specific energy per cow is between 200 and 300 $kWh_{ele}$/y.

### 2.1 Specific energy Improvements

There has been significant reduction in the thermal energy efficiency of milk powder plants since the first oil shock in 1972. Fossil fuel consumption has decreased from 12,000 MJ/$t_p$ of powder to below 6,000 MJ/$t_p$, while electricity use has ranged from 540 MJ/$t_p$ (150 kWh/$t_p$) to 1,440 MJ/$t_p$ (400 kWh/$t_p$). The electricity to fossil fuel split depends on plant technology, degree of heat integration, production run lengths, and utility system efficiency. Overall the wide spread adoption of MVR and TVR technology in multi-effect evaporators has contributed to the significant drop in thermal specific energy levels. Higher milk concentration into the dryer and improved droplet technology has also improved overall energy efficiency. Other energy efficiency improvements include cold milk separation and better integration of cow water for dryer air preheating.

### 2.2 Ultra-low energy milk powder plant – minimum target

The development of an ultra-low energy milk powder plant is an important strategy to creating a sustainable milk powder plant powered by 100 % renewable energy. Previous Pinch Analysis studies demonstrated that 2016 industry specific energy levels are still well above minimum thermodynamic targets (Walmsley et al., 2013). With better placement of vapour recompression technology in the combined heat treatment and evaporation system (Walmsley et al., 2016a) and through dryer exhaust heat recovery (Walmsley et al., 2015b) and chiller waste heat upgrading and recovery, plus using condensing economisers in boilers and CHP where appropriate, ultra-low specific energies of around 2,900 MJ/$t_p$ thermal and 800 MJ/$t_p$ (221.6 $kWh_{ele}/t_p$) electrical are possible (Walmsley et al. 2016). These specific energy levels are much closer to the minimum targets and reducing utility demand closer to these Pinch Targets is an important step toward a sustainable energy solution for milk powder production.

## 3. Methods

### 3.1 Ultra-low energy milk powder plant model

A comprehensive heat and mass balance process and utility model of a 10 t/h ultra-efficient milk powder factory has been implemented in an Excel$^{TM}$ spreadsheet. The model was developed from earlier plant models that had been validated against industrial data from NZ's current milk powder plant design. The ultra-efficient model plant has a thermal demand of 8,039 kW and an electrical demand of 2,216 $kW_{ele}$. These energy demand levels set the required renewable utility supply profiles for the future 100 % renewable energy milk powder plant design.

### 3.2 Renewable utility supply models

Three renewable utility supply mass and energy balance models to meet minimum thermal (8,039 kW) and electrical demand (2,216 $kW_{ele}$) energy levels for a 10 t/h milk powder plant and some on-farm electricity use has been implemented in an Excel$^{TM}$ spreadsheet. The models cover the three case studies and involve six types of renewable energy resources, namely geothermal heat, biomass, biogas, solar thermal and renewable electricity from a hydro, wind and geothermal.

*Table 1: Renewable energy supplies for a 10 t/h future ultra-low energy whole milk powder plant*

| Case study | Plant Location | Renewable Resources | Utility Technology | Renewable Utility Supply |
|---|---|---|---|---|
| 1. | New Zealand<br>Central<br>North Island | Geothermal steam<br>1a. High Temp 224 ºC, 32.5 t/h<br>1b. Low Temp, 170 ºC 54.6 t/h<br>Plus geothermal electrical | Clean steam generator<br>Flash tanks<br>Separator<br>Geothermal power<br>MVR | 1a. HP Steam 23 bar, 9.4 t/h<br>LP steam 2 bar, 5.8 t/h<br>HW 85 °C, 36.5 t/h<br>Plant power 2.3 $MW_{ele}$<br>1b.MP steam 10.5 bar, 11.8 t/h<br>LP steam 2 bar, 3.7 t/h<br>HW 85 °C, 69.6 t/h<br>MVR 0.44 $MW_{ele}$ + 2.3 $MW_{ele}$ |
| 2. | New Zealand<br>Central<br>North Island | Green wood 4.4 t/h<br>Forest land 42,709 ha<br>Wind, Hydro electricity | Biomass boiler<br>Heat pumps | HP steam 40 bar, 13.4 t/h<br>HP 0.9 $MW_{ele}$ + 2.3 $MW_{ele}$ |
| 3. | California<br>Central valley | Cow manure to Bio- methane 49.5 GJ/h<br>60,000 cows<br>37 % manure collection<br>Solar collector area 16,680 $m^2$ | Anaerobic digester water scrubbing<br>Two stage compressor<br>CCGT and HRSG<br>Solar thermal collectors, 5,000$m^3$ thermal storage | Biogas – CGT HRSG<br>Electrical 3.3 $MW_{ele}$<br>HP steam 40 bar, 13.4 t/h<br>Solar Thermal utility<br>HTHW 1,554 MW<br>CTHW 531 MW |

## 4. 100 % renewable energy milk power plant case studies

This section reports on the three case studies (1) geothermal for high and low temperature reservoirs, plus renewable electricity, (2) biomass, heat pumps and renewable electricity and (3) biogas and solar thermal.

### 4.1 Geothermal steam supplied utilities

Two different options for supplying heat to the model powder plant with geothermal heat are shown in Figure 1 and Figure 2 for a high and low temperature geothermal resource. Geothermal fluid is typically extracted as a two-phase mixture of liquid and steam. To produce clean steam the fluid is first passed through a separator, with the steam being used to produce clean steam. The separated saturated fluid can then be flashed and the steam used again to produce lower pressure clean steam. Temperature constraints will require smaller approach temperatures on dryer inlet air heat exchangers, changes to inlet conditions or supplementary higher temperature heating via combustion of biomass/biogas or electrical heating. This is a cost optimisation problem that will be examined in future work.

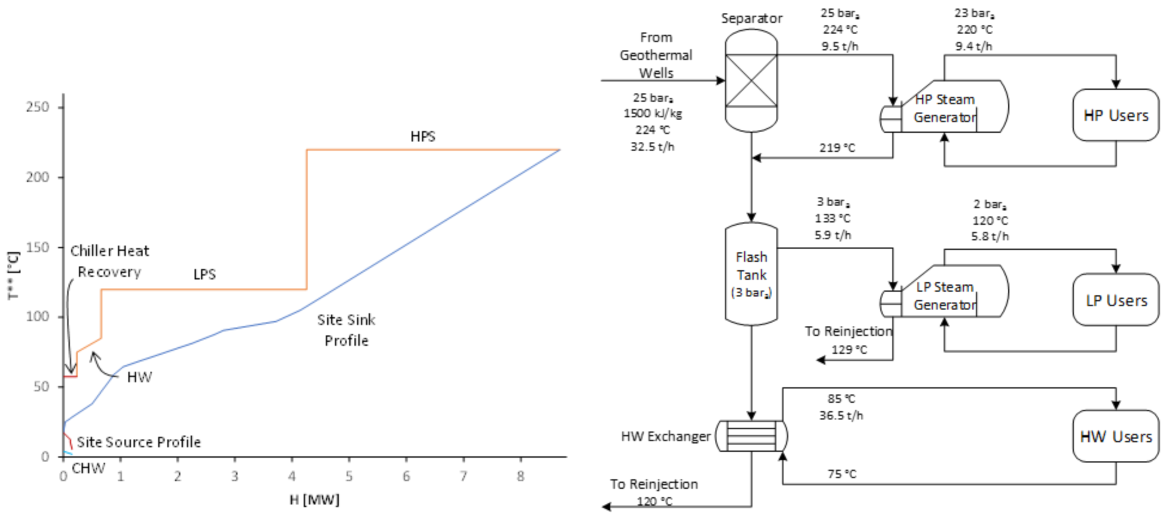


*Figure 1: High temperature geothermal reservoir*

For low temperature geothermal resources, where temperatures are approximately 170 °C, MVR technology can be utilised to upgrade the clean steam temperature (Figure 2). In this case a 4-stage MVR system is

needed, but to produce air at 180 °C for the dryer inlet a smaller approach temperature is required, as in the situation for the high temperature case. Due to the restriction in the maximum temperature of the geothermal fluid, changes in the process temperatures, and in this case the dryer inlet air temperature, need to be examined. It is possible to produce milk powder at dryer inlet temperatures of around 180 °C but more air is required, the functionality of the powder is altered, and the dryer operates at a lower efficiency.
When there are constraints on the maximum utility temperature available, like with the low temperature reservoir, changes in process conditions need to be considered, or alternatives found for providing increased temperatures. Again this is a cost optimisation problem that also requires careful examination on the effects on milk powder properties and functionality.

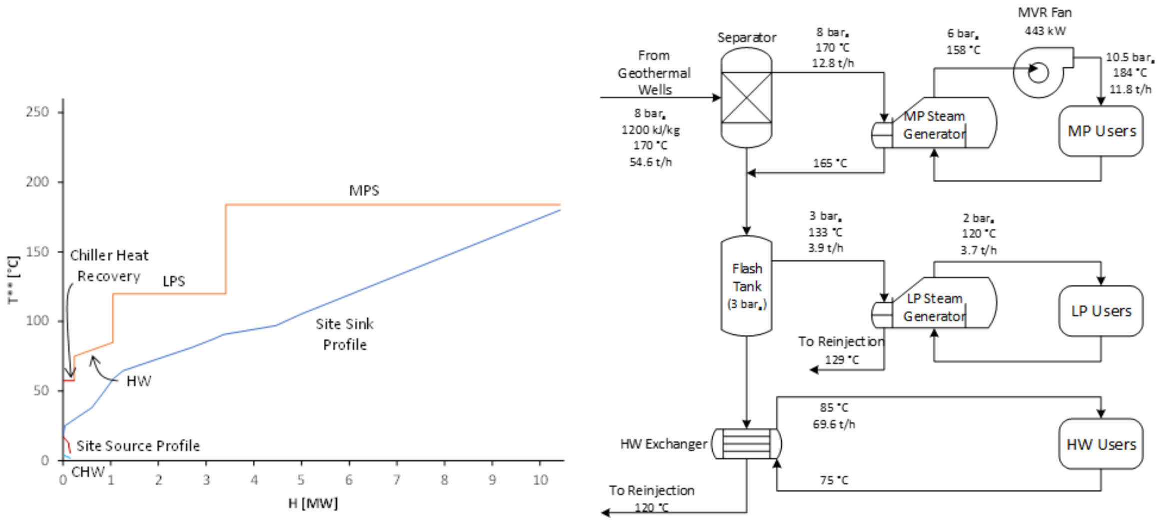


*Figure 2: Low temperature geothermal reservoir*

For both reservoir cases, it is proposed that the 2.2 $MW_{ele}$ of plant electrical demand is met 100 % by geothermal electricity available in plentiful supply in the Central North Island region of New Zealand. Geothermal made up 16 % of New Zealand's electricity generation in 2015 with 1,010 $MW_{ele}$ installed capacity, and a further 840 MW is identified as upcoming developments by 2025 (White, 2016).

**4.2 Biomass and heat pump supplied utilities – non-geothermal regions of New Zealand**
The second renewable utility supply investigated for New Zealand is biomass energy complemented with renewable electricity heat pumps. With supplies of biomass being at a premium in a post fossil fuel scenario and renewable electricity supply being more readily available from hydro, wind and geothermal sources, the economics of medium temperature heat pumps will likely be favourable. Figure 3 presents the cycle (A) and heat demand profiles (B) of a two-stage ammonia heat pump with internal inter-cooling. The estimated Co-efficient of Performance (COP) of the heat pump is 2.56. The evaporator of the heat pump is supplied by the biomass boiler flue gas, while the condenser generates the required LTHW and HTHW utility demands. Including chiller heat recovery, heat pumps supply a combined 2,322 kW of heat (26.7 % of thermal demand).
The remaining 73.3 % of heat (6,363 kW) is supplied by a biomass boiler as shown in Figure 4. The biomass boiler generates 40 bar steam, which may be let-down to other pressure levels where required in the plant. The estimated boiler efficiency is 80.1 %, which is substantially lower than 91.6 % efficiency that can be achieved by a natural gas boiler with condensing economiser (Walmsley et al., 2016).
The cost of biomass collection and transport is an important economic consideration. Fortunately numerous areas of New Zealand have wood resources either from plantations, farm blocks, and/or processing residues. Biomass can also be grown directly on dairy farms as trees in a mixed land use strategy. A few extra trees for bioenergy production may not reduce milk production. Trees on dairy farms, prevent erosion, provide shade to animals, reduce water loss through evaporation, plus provide addition income for the farmer. However, large coverage of trees will reduce herd numbers and hence milk production, and therefore extra land close to the powder factory will need to be set aside for biomass energy.
Approximately 4.4 t/h of green wood residues are needed to meet milk powder processing requirements. Typical New Zealand annual tree stocking rates of 20 $m^3$/ha mean that a farm of 150 ha would need an extra 52 ha (35 %) of forest farm area for bioenergy production, which is considerable. If the biomass were to come from plantation forests, then a 35 % residue rate for a forest the same size as the all the 283 dairy farms (150 ha/farm) would be needed to supply the factory with enough bioenergy.

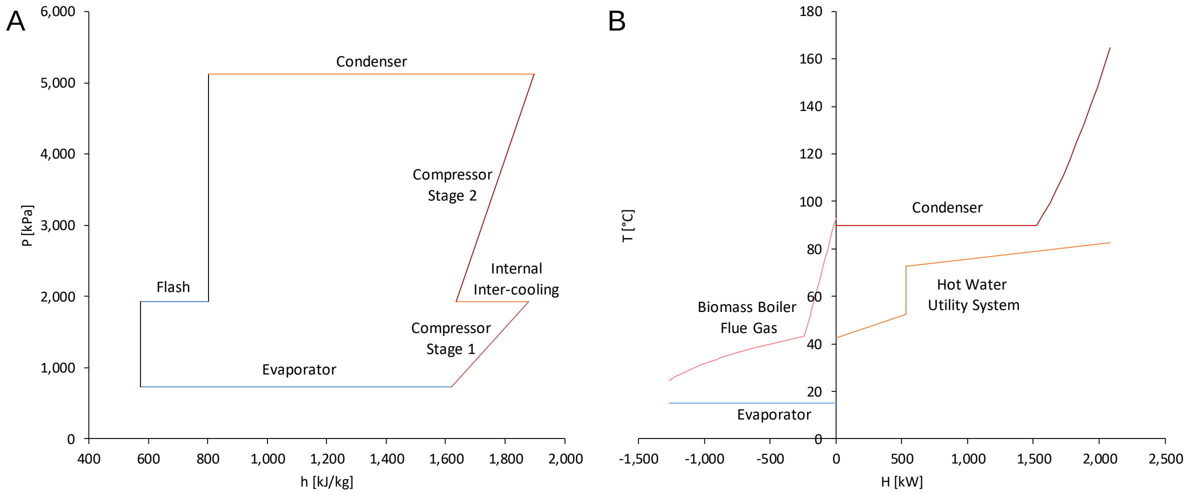


*Figure 3: Two-stage ammonia medium temperature heat pump for upgrading boiler flue gas heat*

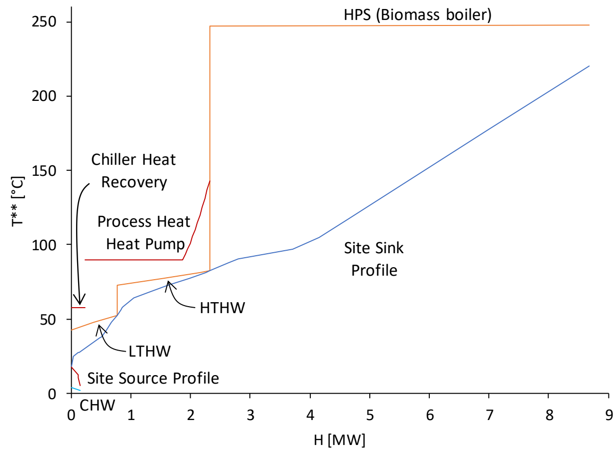


*Figure 4: Biomass boiler and renewable electricity supplied heat pump utilities with Total Site Profiles*

### 4.3 Biogas and solar thermal – Central Valley California

The third renewable utility supply option investigated is for a milk powder plant located in California's Central Valley where there is an abundance of sunlight and intensive dairy farming with irrigation. The valley produces 19 billion litres of milk per year, which makes up 20 % of US milk. Dairy herds of up to 2,500 animals are packed into outdoor pens and fed corn silage and alfalfa as the primary feedstock. The high density animal containment method is ideal for collecting cow manure and for making renewable biomethane via anaerobic digestion and water scrubbing to remove $CO_2$ on farm (Noorollahi et al., 2015). To help the economics biomethane needs to be compressed to 200 bar on farm and transported by CNG type tankers to the milk powder factory, which is estimated to be an average distance of about 25 km.

For a 10 t/h milk powder plant, 60,000 cows spread over 24 farms are required to supply the raw milk. The same number of cows produce enough manure to generate 49.5 GJ/h of biomethane at a modest collection rate of 37 %. The biomethane fuels a combine cycle gas turbine with HRSG to produce 6.36 MW thermal, as shown in Figure 5, and 3.3 $MW_{ele}$ electrical, which covers 2.3 $MW_{ele}$ in factory use and 1 $MW_{ele}$ on farm for biogas water scrubbing and compression from atmospheric pressure to 200 bar.

For solar thermal generation, two hot water utilities are required, namely; 768 kW of LTHW at 55 °C and 1,554 kW of HTHW at 85 °C, again shown in Figure 5. The LTHW is heated by 237 kW of chiller heat recovery and 531 kW from solar. Both HW utilities can be heated by solar collector area of about 16,680 $m^2$ assuming an average radiation of 0.25 kW/$m^2$. LTHW utility loop operating with ΔT of 10 °C will require storage of about 1,000 $m^3$. With increased ΔT of 20 °C volume can halve. Similarly for the HTHW utility loop, storage volume is very large at 3,200 $m^3$ for a ΔT of 10 °C. A large ΔT is preferable but the value is limited by the Total Site Profile. A detailed cost optimisation is required to find the best balance between solar thermal and biomethane production. For example, improving manure collection to 50 % would mean solar thermal is not needed, and this may be a cheaper option. This will be the subject of future work.

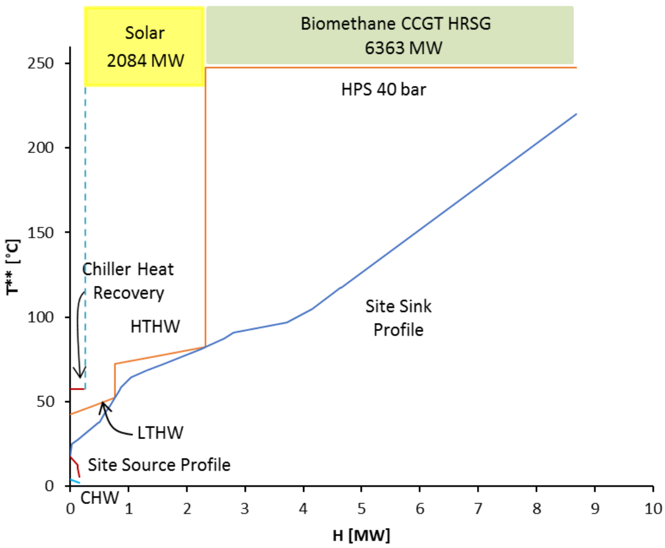


*Figure 5: Combined cycle gas turbine with HRSG and solar thermal hot water utilities with Total Site Profiles*

## 5. Conclusions

Complete renewable energy supply to a 10 t/h milk powder plant can be achieved in the Central North Island of NZ through utilisation of 54.6 t/h of low or 32.5 t/h of high temperature geothermal steam, combined with 2.3 $MW_{ele}$ of renewable electricity for plant needs and 0.44 $MW_{ele}$ for steam temperature upgrading using an MVR. Where geothermal is not available (i.e. outside Central North Island of NZ) a combination of 4.4 t/h of biomass in a boiler and 0.9 $MW_{ele}$ renewable electricity for heat pumps can supply the process heat requirements and 2.3 $MW_e$ for the plant is again from renewable electricity. In California biomethane from manure is a viable options due to the intensive dairy farming methods used. 60,000 cows, from 24 farms, with a 37 % manure collection rate can produce enough heat to power a CCGT and HRSG to supply 75 % of thermal energy needs above 80 °C and 100 % of the electricity needs including 1 $MW_{ele}$ for Biomethane compression on farm prior to transportation to the factory. The remaining 25 % thermal (below 80 °C) can be done using solar thermal, however collector area is substantial and very large storage volumes are also required to cover day-night variation. Improving manure collection to 50 % may be a better alternative to solar thermal. Options for achieving the goal of a 100 % renewable energy milk powder plant are very geography dependent and process conditions may need to be modified to enable high uptake of renewables.

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