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Research article

Investigating off-grid systems for a mobile automated milking facility

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ABSTRACT

This study examined the potential of renewable energy sources to provide the necessary power for a mobile off-grid automated milking system (AMS) and associated facilities on pasture. This involved choosing the most cost-effective, environmentally friendly, and sustainable power supply for a mobile AMS in Sweden operating May–September and milking 20 cows per day. Weather data, input from the milking system manufacturer (DeLaval), and outputs from two mathematical models, Insight Maker and HOMER, were used to investigate the potential of different renewable energy sources (biodiesel-, ethanol-, or biogas-run generators, solar photovoltaic (PV) panels + batteries) to support the mobile system. Solar-based energy best fulfilled the key requirements of being environmentally friendly, cost-effective, and sustainable. It also gave the lowest net present cost (11,804 USD), levelized cost of energy (0.31 USD), and annual operating costs (178.26 USD) of all renewable energy options considered. Thus use of solar PV panels + batteries is recommended for the mobile AMS facility. Ways of addressing possible challenges that could arise during implementation, uncertainties in input parameters, and limitations in scaling-up and replicating the proposed set-up are discussed.

1. Introduction

Interest in fully automated milking systems (AMS) dates back to the 1970s. The main driver for adopting such systems, which were first developed in Europe, was the overall growing burden of labor costs associated with the milking process. A decade later, reliable and fully integrated AMSs became a reality. In essence, this involved automating all functions of the milking process and cow management (i.e., motivation to visit the AMS) [1]. Today, AMS are accepted internationally as a valid alternative to the conventional milking parlor and an advanced means for dairy farm management. In the past decade, 8,000 farms worldwide have installed AMSs [2, pp. 736–741].

Developing mobile systems for AMS technology is now becoming a highly encouraging path. So far, research on mobile systems has been conducted in countries such as Belgium, Denmark, France, and the Netherlands. The level of mobility studied ranges from systems being moved a few times a year to daily movement [3]. Table 1 lists key prototypes developed to date, none of which uses an off-grid renewable power source [4].

Initial findings on adopting the mobile set-up indicate the advantage of milking cows in the field without additional labor, which allows the cows to spend more hours on pasture. This provides fresh air for the cows, increases intake of feed from pasture, reduces the need for manure handling, and results in natural fertilization of soil [[5], pp. 402–407]. Flexibility in land use is another key advantage, especially for landowners, with high potential for new entrants in lease or share-farming arrangements [3]. Moreover, the mobile set-up in pasture allows more fields, not necessarily close to farm centers or barns, to be grazed by the cattle. Properly managed grazing improves cow wellbeing and also increases soil biological activity, resulting in highly productive pastures and better cycling of nutrients within the soil, a significant factor for plants and other soil life [6].

However, many factors still need to be thoroughly investigated before full integration of pasture-based milking facilities in general, and mobile milking in particular. These include the economics of milking, pasture availability and management, and the practicalities of installing and managing the AMS on-site. According to a review of 21 previous studies on pasture-based milking, a common persistent challenge is low milking frequency (MF) [7], which has been attributed to low cow traffic. Thus further research is needed on the frequency and location of feed incentives.

Tests conducted by the University of Liége in 2010 comparing indoor and pasture-based milking revealed clear differences in milk yield between the two systems [8]. Preliminary findings on using a mobile AMS were as follows: "*The cows were easily accustomed at milking robot indoors and their milk production increased. During the indoors period (60 days), they*

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Table 1. Mobile automated milking system (AMS) prototypes developed to date [4].

Organization, country	Year	No. of cows	Characteristics
Århus University, Denmark	2007	90	Installed in a standard container. Water provided by pipe, electricity by generator.
University of Liége, Belgium	2010	45	Installed on a trailer with an electric point.
Trévarez farm, France	2012	45–60	Installed on a trailer.

*produced 29.*5 kg *milk per day (173 days in milk), the mean number of milking was 3.09 and there was 1.06 milking refusal per day. During the period at grass (50 days), the daily milk production was 21.*1 kg *(215 days in milk), the mean number of milkings was 2.12, and the milking refusal was 0.22"* [8].

Owing to the limited research to date and the short history of mobile AMS adoption on pasture, there are still many aspects concerning the technology, associated animal behavior, and surrounding environment that remain to be explored. Using the example of a dairy farm in Sweden, this study sought to contribute to current knowledge by examining the potential for integrating off-grid renewable systems into mobile AMS facilities on pasture worldwide. Key drivers of this proposed development were:

- *Enhancing self-resilience*: There is no need to rely on a stationary power point or connection to receive the necessary power supply to run the AMS, so there are no limits to the mobility of the set-up or limitations in logistics.
- *Sustainable and renewable sources of energy*: Exploring several power source options that would suit a mobile AMS in terms of environmental impact, costs, and availability.
- *Addressing research gap*: The lack of previous research on power sources for an off-grid AMS makes the study significant and unique.
- *Transition of energy:* Off-grid renewable energy capacity has achieved a spectacular three-fold increase, from under 2 gigawatts (GW) in 2008 to over 6.5 GW in 2017 [9]. A proportion of deployed capacity supports household electrification, but the majority (83%) supports industrial (e.g., co-generation), commercial (e.g., powering telecommunication infrastructure), and public (e.g., street lighting, water pumping) end-uses [9]. Mobile AMS can certainly benefit from the rapid diffusion and advance of off-grid renewable systems.

The specific objective of this study was to compare renewable energy sources that could provide the necessary power for a mobile off-grid AMS. This involved choosing between various sources, with considerations heavily weighted on the cost-effectiveness, environmental impact, and sustainability of the energy source within the given environment and the potential for utilization. The mobile AMS was assumed to milk a total of 20 cows per day during spring-summer and the AMS equipment was assumed to be housed in a 30-foot (9.14 m) cargo container.

2. Methodology and approach

2.1. Location for the study

Facilities at Lövsta research center, Swedish Livestock Research Center, were used for the study. Lövsta has different farms for dairy cattle, pigs, and poultry, and runs a biogas plant which provides self-sufficiency in both electricity and heat for all the farms. A group of 250 lactating cows is milked in an AMS (DeLaval VMS) [10]. In this study, it was assumed that the mobile AMS integrated with an energy system could be placed on any pasture, milking 20 cows per day.

2.2. Stationary system and modifications for the mobile AMS

The DeLaval voluntary milking system (VMS300) used on the Lövsta dairy farm is designed to provide a complete AMS in a cow-friendly, hygienic, and efficient way. The main components of the system are shown in Figure 1.

In addition to the main components illustrated in Figure 1, other essential units connected to the VMS300 station are a milk tank, vacuum pump, compressor, ventilator, and chiller. Main tasks include providing feed to the cow upon entry, extracting an equivalent of 45 s of pre-milk, cleaning the cow teats and drying these prior to actual milking, conducting the actual milking and transferring milk to the designated tank, post-milking cleaning of the cow's teats, and cleaning of the entire deck station with its components (teat cups, multi-purpose arm, etc.).

One key issue for this study was identifying total energy consumption by the AMS and its associated components. Through direct correspondence with the manufacturer DeLaval and from their research data from other sites within Sweden, it was established that the total energy consumption was represented by four main components: (a) the AMS itself (VMS300), (b) the vacuum pump, (c) the compressor, and (d) the cooling system (Table 2).

Total energy consumption values were converted to represent 500 and 400 kg of milk produced and the associated kWh per day (11.0 and 9.0, respectively) (Table 3).

Based on the above information and considering the requirements for the mobile AMS set-up serving 20 cows on pasture, total energy load was estimated to be 9.0 kWh per day (Table 3).

2.3. Considered Renewable energy sources

Prior to assessment of potential set-ups, it was important to identify appropriate renewable energy sources to be considered. Factors such as site weather conditions, the surrounding environment, and practicalities in general formed the basis for this choice.

Weather data were taken from different weather databases such as LantMet and from websites such as weatherspark [14]. For the purpose of this study and due to the clarity and simplicity of weatherspark plots, preliminary conclusions on weather conditions were derived from these graphs. The commonly used renewable energy types considered were solar, wind power, and biomass energy, which are all commonly used in off-grid setups and provide rather low costs per kWh. Another factor was abundance of the primary energy source (i.e., solar radiation, wind, biofuel).

These renewables were compared to determine which suited the mobile AMS best. Table 4 shows the parameters by which these three renewable energy types were compared and shortlisted for further investigation. The parameters were intended to provide a first impression of the renewable energy types, showing how cost-effective, sustainable, and practical each was for the particular case studied. For instance, parameters such as *availability of energy sources* and *abundance of primary energy sources* indicated the sustainability of the renewable energy type and the corresponding energy source. The *minimal environment impact* parameter helped demonstrate the environmental aspects. In terms of cost-effectiveness, *overall cost per kWh* was a useful parameter. An important characteristic considered was the practicality of the renewable energy types in terms of installation and mobility, which was assessed using the parameters *practicality* (in *set-up installation* and in *mobility in operation*) to identify possible shortcomings.

Solar power was found to be the most promising renewable energy type of the three, with biomass energy (biofuel) the second best option (Table 4). All three renewables have abundant primary energy sources (i.e., wind, solar radiation, biomass) and can function within the

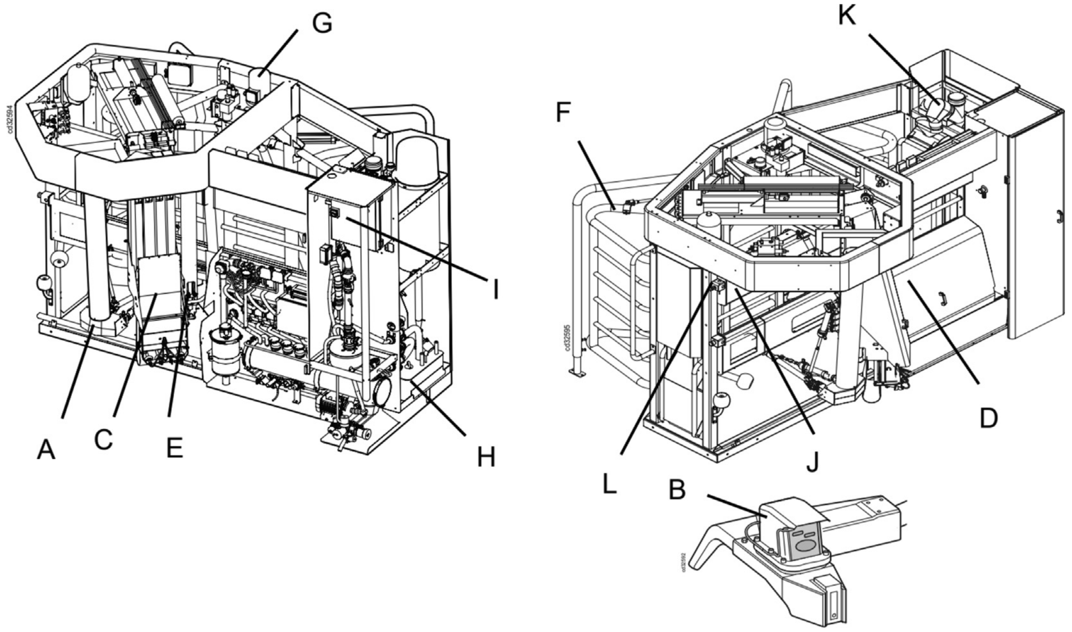

Figure 1. Main components of the DeLaval Voluntary milking system. A) Multi-purpose arm, B) camera unit, C) magazine, D) milking module, E) teat preparation module, F) stall and gates, G) hydraulic pump unit, H) cleaning unit, I) power box, J) electrical box, K) feeding module, and L) services switch [11].

Table 2. Total energy consumption by the four main components of the automated milking system considered in this study [12, 13].

Component	Energy consumption (kWh) per 24 h	Energy consumption (kWh) per 1000 kg milk	Rated power (kW) per 1000 kg milk	Peak power (kW)
VMS300	8.94	2.79	3.11	1.52
Vacuum pump	17.40	5.44	7.41	1.88
Compressor	15.98	4.99	5.54	6.28
Cooling system	22.40	7.00	8.53	2.50
Total	64.72	20.22		

Table 3. Energy consumption expressed in kWh per day [12, 13].

Type	kWh	Typical Number of cows	kWh per day
Full capacity	65.00	140	65.00
1000 kg milk	21.00	50	21.00
500 kg milk	10.50	25	11.00 [1]
400 kg milk	8.40	20	9.00 [1]

[1] Values rounded up.

Table 4. Comparison of renewable energy (RE) types, where G is Good; A is Average; and P is poor).

RE type	Availability of energy source	Abundance of primary energy source	Applicable in given environment	Practicality in set-up installation	Practicality in mobility in operation	Minimal environment impact	Overall cost per kWh
Solar	G	G	G	G	G	G	A
Wind	A	G	G	P	P	A	G
Biomass	A	G	G	G	G	A	G

surrounding environment. However, some parameters indicated lower reliability in some areas, e.g., availability of the energy source on-site during the study months (i.e., Lövsta/Uppsala area, May–September). From weather data for the study area, it was concluded that solar power was best suited, with longer days and the highest solar energy potential during the intended operational period. Wind speeds would undoubtedly drop during the same period, while the absence of a nearby biofuel filling station (except for biogas supply) within the Lövsta area was a disadvantage. For these reasons, biomass and wind power scored lower score in terms of availability of their energy source (Table 4).

With regards to practicality in set-up installation and in mobility in operation, wind power scored lowest, because a mobile wind turbine would not be feasible, and it would not be practical to have a stationary turbine connected to the mobile AMS.

The score for both biomass and wind power within the minimal environmental impacts category was average, rather than good, because the biodiesel generator creates noise and pollution, and wind turbines create risks for birds. The overall general cost was also a significant parameter to take into consideration. According to the US Department of Energy, wind and biomass have relative lower average cost (0.04–0.12

USD per kWh) than solar (0.21–0.81 USD per kWh) [15, pp. 242–243]. Thus solar power scored lower for this parameter.

Based on the above, only solar energy and biomass energy were considered in further comparisons of their reliability and success in providing power to the mobile AMS. There are many types of biofuels to choose from (ethanol, methanol, biogas, biodiesel, etc.). However, the aim in the analysis was to identify and compare fuel(s) which are readily available, environmentally friendly, and practical to use with a mobile AMS set-up. The following characteristics were considered when choosing biofuels for further investigation:

- *Readily available*: Availability of fuel (an integral component) is significant, as it affects the sustainability of the whole AMS system. Biogas, ethanol, and biodiesel are accessible within the Lövsta farm area. Ethanol (E85) and biodiesel (B100) are available from filling stations in the nearby Uppsala city, while biogas may be even more readily accessed within the vicinity of the farm, if the locally produced gas there was found to be useful and suitable for the AMS. Methanol on the other hand is not available in the area.
- *Practicality in usage*: With the mobile AMS to be installed inside a 30-foot cargo container, finding room for the power generator and other accessories was a challenge. Therefore, it was important that the fuel set-up occupied little space. This implies that liquid-state fuels (at room temperature and pressure, RTP) may be favorable for the purpose. Biogas at RTP would occupy more room, due to the need for a reformer or storage of the fuel itself (e.g., gas cylinders). Thus in terms of practicality in usage, ethanol and biodiesel appeared to be more favorable.

Based on the above characteristics, especially availability of the biofuel, ethanol, biodiesel, and biogas were selected for further analysis.

2.4. Software tools and approach

The analytical approach adopted in the study comprised use of two existing models. The Insight Maker (IM) model was used for presentation and the Hybrid Optimization of Multiple Energy Resources (HOMER) model was used for identifying feasible configurations and power source options (i.e., solar photovoltaic (PV) panels + batteries, biofuel + generator). The environmental and sustainability impacts of feasible configurations within the anticipated AMS environment and level of operation were then assessed. Consideration of both impacts helped identify the most suitable off-grid system for the mobile AMS (Figure 3).

The modeling work required a wide range of information. The data used and their source were as follows:

- *Identified loads*: The manufacturer of the stationary AMS currently used at Lövsta and of the potential mobile AMS (DeLaval) provided vital data on energy consumption levels (per day and per kg) of the key components in question (see Tables 2 and 3).
- *Considered Renewable energy sources*: Suggested material costs and operation and maintenance (O&M) costs for the biofuel-generator types and solar PV-batteries renewable energy systems were sourced within the HOMER software or sourced locally.
- *Operation parameters*: Data were obtained directly from the Lövsta farm. Typical key data included: Anticipated number of cows milked per day, months of operation for the mobile AMS, location of the farm where grazing will take place, and project lifetime.
- *Environment and sustainability:* Information on the mobile AMS housing container and on feed and water consumption levels on Swedish farms was used in assessing other factors concerning practicalities and potential risks of the proposed renewable energy systems regarding surrounding environment and set-up.

2.4.1. HOMER software and parameters

The HOMER model was the key tool used in assessing renewable energy sources for the mobile AMS. The software, which was originally developed at the National Renewable Energy Laboratory (NREL), combines three powerful tools in one product, so that engineering and economics analyses work side by side [16]:

- *Simulation*: The software stimulates a viable system for all possible combinations of the equipment that the operator would wish to consider.
- *Optimization*: All possible combinations of system types are examined in a single run and sorted according to the optimization variable of choice.
- *Analysis:* Impacts of how variables such as wind speeds, fuel costs, etc. may change and affect optimal systems through time are assessed.

The HOMER software is able to provide thorough, highly reliable, yet quick estimates of designs for both off-grid and grid connected systems composed of various types of modules (from both renewable and non-renewable sources).

2.4.1.1. Input data. The two main renewable energy sources identified as suitable for the mobile AMS set-up were modeled using the HOMER software. Input data to HOMER were study area coordinates (59.5°N, 18.2°E), reflecting the climate conditions there, and the following key data:

- Electric load: 9.0 kWh per day
- Load season months: May, June, July, August, and September
- Load time chosen: From 11:00 to 16:00 h (5 h)
- Load lifetime-project life: 25 years

To enable the software to present the best possible combination(s) to match the energy requirements for the mobile AMS set-up, the following input data were provided for solar PV + batteries and biofuels:

2.4.1.1.1. Solar PV + batteries. Key components of solar PV + batteries from different manufacturers, models/types, and capacities were selected from the HOMER library. Selection of the components was based on their key characteristics, which were assumed to meet the estimated energy load for the system. Key components were:

2.4.1.1.1.1. Photovoltaic panels

- 330 W capacity PV model Canadian Solar Max Power CS6U–330P flat plate with 72 poly-crystalline cells (6 × 12). PV dimensions: 77.2 × 39.10 × 1.57 inches (1.96 × 0.99 × 0.04 m) [17].
- Capital cost: 345.00 USD, replacement cost: 345.00 USD, total O&M cost: 5.85 USD/kW-yr, derived from: General site maintenance cost (0.20–3.00 USD/kW-yr), wiring electrical inspection (1.40–5.00 USD/kW-yr), panel washing (0.80–1.30 USD/kW-yr) [17].

2.4.1.1.1.2. Battery

- 9.27 kWh capacity, BAE $_{\text{SECURA}}$ PVV solar, Model: BAE PVS 4940 [18].
- Capital cost: 1,121 USD, replacement cost: 1,121 USD, total O&M cost: 5.60 USD/yr (suggested 0.5% of capital cost) [18].

2.4.1.1.1.3. Inverter (bi-directional)

- Leonics S-219Cp 5kW or rated power 5.5kW and a nominal voltage of 48 vdc [19].
- Capital cost: 900 USD, replacement cost: 900 USD, total O&M cost: 4.50 USD/yr (suggested 0.5% of capital cost) [20].

Before running the software with the chosen components using the "*Search space*" function, the range of options from which HOMER could choose was set as follows:

- Total PV module capacity: 1–10 kW
- Total number of batteries: 1 to 5
- Total Inverter capacity: 1–10 kW

The sensitivity analysis option within the software was set only for the lifetime section. Options available for simulation included 10, 15, 20, and 25 years of time.

According to NREL [21], typical solar PV emissions are 40 g CO_2 per kWh. Since HOMER models emissions only for generators, boilers, and reformers, the levels of emissions for the solar PV + batteries set-up was investigated by other means.

2.4.1.1.2. Biofuels. In order to make simple yet valid comparisons between different biofuels and solar PV + batteries, four key parameters were checked for every simulation (fuel curve, fuel price, capital costs, and levels of emissions). Details of these parameters and the approach adopted were as follows:

- *Fuel curve*: This describes the amount of fuel the generator consumes to produce electricity. HOMER assumes that the fuel curve is a straight line and suggests this within its advanced properties option. The following equation gives the generator's fuel consumption in units/hr as a function of its electrical output:
  F_0 = Fuel curve intercept coefficient (units/hr/kW)
  F_1 = Fuel curve slope (units/hr/kW)
  Y_{gen} = Rated capacity of the generator (kW)
  P_{gen} = Electrical output of the generator (kW) [22].
- *Fuel price*: This is an input variable typically expressed as USD/L. In this project, it was chosen to meet Sweden's current fuel markets and prices.
- *Capital costs*: These include the generation cost, replacement cost of the generator, and annual O&M costs. To simplify comparisons between the various liquid-state fuels, capital costs were kept exactly same for all. Using a basic diesel generator as reference to these costs served two functions: i) achieving a unified cost to allow comparison on other parameters and ii) all fuels considered can be actually used, with minor adjustments, in a common diesel generator. With regard to the biogas generator, which uses fuel in gaseous state at RTP, a different data source was used.
- *Levels of emissions*: These are calculated by HOMER software and in most cases the value is already set as a default. In this analysis, only CO_2 emissions were considered.

The biofuels simulated by HOMER are described below. Suggested values for generators and fuel prices reflect the Swedish markets, while O&M costs were provided as default by HOMER.

2.4.1.1.2.1. Ethanol and biodiesel

The fuel prices for HOMER simulations were sourced from a nearby filling station (June 2020 rate) [23] and the capital costs were for a three-phase Swedish 12.5 kVA diesel power generator [24] 29,995 Swedish Krona (SEK) (3,258 USD). This gave (3,258 USD/12.5 kVA) = 260 USD per kW, which was rounded up to 300 USD per kW. Replacement of the generator after 15,000 h of operation used the same rate cost, 300 USD per kW. To enable HOMER to run the simulations properly, all input values, including Swedish fuel prices, were converted to HOMER's default currency of USD. For ethanol and biodiesel prices of 10.89 SEK and 14.87 SEK/L [23], this gave an input value of 1.18 and 1.61 USD/L, respectively. Finally, the O&M costs (default HOMER values) were 0.03 USD per operating hour.

2.4.1.1.2.2. Biogas

A 10 kW biogas electric generator costing 3,650 USD was considered [24]. In terms of initial capital, this equated to 365 USD per kW. Replacement after 15,000 h of operation used the initial capital rate (365 USD/kW). Biogas price according to e.on was 17.29 SEK per kg [25], or 1.88 USD per kg. To allow for comparisons based on other parameters, the O&M costs were the same as for other biofuels (0.03 USD per operating hour).

2.4.1.1.2.3. Diesel (a benchmark)

To provide a point of reference for further comparison, the non-renewable fuel diesel was also simulated in HOMER, assuming the same power generator and associated costs as for biofuels. The only difference was the fuel price, which was 14.13 SEK (1.54 USD) per liter.

2.4.1.2. Main parameters for evaluating HOMER results. The evaluation of HOMER results focused on three main parameters, to allow level of cost-effectiveness and environmental impact of the systems to be compared.

- Net Present Cost (NPC): The NPC (or life-cycle cost) of a component is the present value of all costs of installing and operating the component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. HOMER calculates the NPC of each component in the system, and of the system as a whole [26].
- Levelized Cost Of Energy (LCOE): HOMER defines LCOE as the average cost per kWh of useful electrical energy produced by the system [27].
- Emissions Outputs: The 'Emissions' tab in the 'Simulation Results' window in HOMER shows the total amount of each pollutant produced annually by the power system, in kg/yr. Pollutants originate from consumption of fuel and biomass in generators, the boiler, and the reformer, and from consumption of grid power. Pollutants consist of carbon dioxide, carbon monoxide, unburned hydrocarbons, participate matter, sulfur dioxide, and nitrogen oxides [28].

2.4.1.3. Overall limitations of HOMER. The main shortcomings in HOMER simulations for the study case related to limitations in time and resources. These prevented a more thorough study with more accurate assumptions and values used in the simulations. Examples of limiting factors included difficulty in predicting costs of materials and fuel prices over a long period (25 years), studying the choice of materials in depth, including more varieties of biofuels, and incorporating emissions of other greenhouse gases (GHGs).

2.4.2. Insight Maker model

The Insight Maker model [29] shows the aggregated operations of a system on macro-scale and cuts away unnecessary detail, allowing a focus on what is truly important in a system [27]. The software was used here to represent and reflect how these are divided between the key components of the AMS. Using the set of figures presented earlier for energy consumption levels, an illustration was created using the Insight Maker (IM) model. Since energy consumption is a key factor in designing the optimum mobile AMS system, it was important that the consumption rates (kWh per day) and the corresponding components of VMS300, namely, the vacuum pump, compressor and the cooling system were clearly presented. Figure 2 shows energy consumption by the 4 main components in an Insight Maker plot that illustrates energy flow from today's existing energy supply within the stationary AMS and how this is divided amongst the 4 key components. Rates of consumption for each component are indicated by the various oval shapes (e.g., Energy Consumption-1-kWh).

2.4.3. Methodology chart

Figure 3 depicts the holistic approach used in studying the feasibility of the mobile AMS. The HOMER and Insight Maker models showed the magnitude of energy consumption, level of associated costs, and emissions to the environment. Considering other significant factors, such as the environmental friendliness and sustainability of the AMS-renewable energy set-up, provided even greater insights and hence a better picture of the system and the best choice of renewable energy source.

3. Results and discussion

Figure 4 depicts the IM model illustration discussed earlier (Figure 2). The energy consumption for each of the components at both full capacity

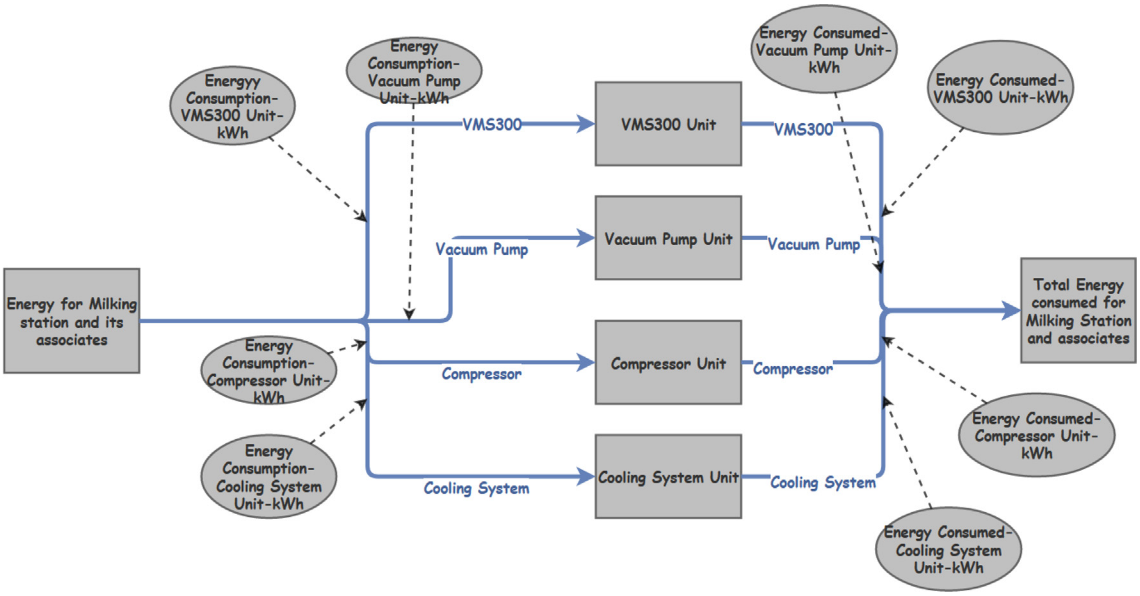

Figure 2. Typical energy consumption for AMS facility (VMS300) and Associates.

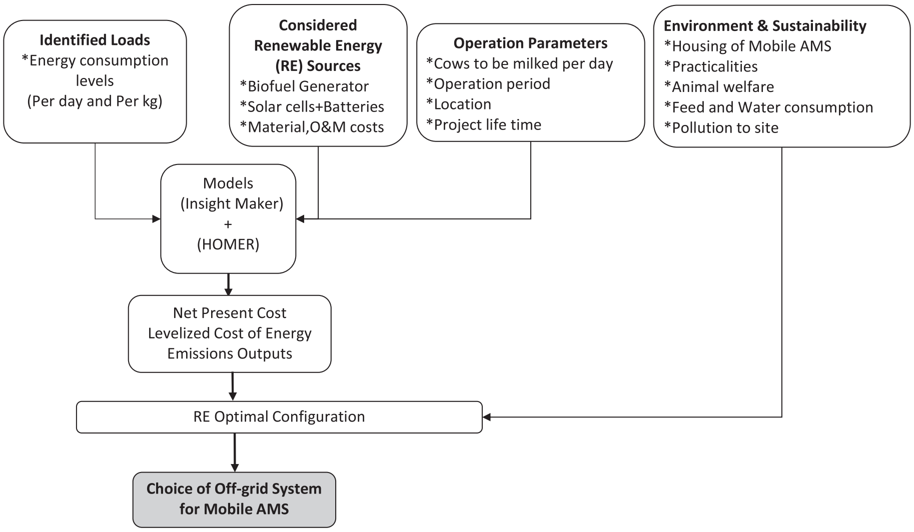

Figure 3. Flow chart showing the methodological approach used in the study.

and at the 400 kg milking capacity is reflected. At full capacity, the anticipated energy consumption levels by the end of the day were estimated to be 8.94, 17.40, 15.98 and 22.40 kWh for the VMS300, vacuum pump, compressor, and the cooling system units respectively. At 400 kg capacity, the levels were estimated to be 1.25, 2.42, 2.22, and 3.11 kWh respectively. Adding up the energy levels for the components at both these capacities gives total energy required by the end of the day (see Figure 2). For the full and 400 kg capacity, this was 64.72 kWh (8.94 + 17.40+15.98 + 22.40) and 9.0 kWh (1.25 + 2.42+2.22 + 3.11), respectively.

The outcome of HOMER simulations on the main deciding factors (i.e., NPC, LCOE, and CO_2 emissions) are provided in Table 5. The simulation results for solar PV + batteries revealed that the following combinations gave the lowest NPC and LCOE values, and hence were the best option for those two criteria:

- 5.04 kW total PV capacity, which equates to 5,040 W/330 W = 15.27 PV panels (i.e., 16 Panels of the 330 W capacity). In terms of area, this equates to 16 × 1.96 m = 31 m^2
- Three 9.27 kWh batteries of type $\text{BAE}_{\text{SECURA}}$ PVV solar
- 1 inverter of rated power 4.83 kW
- 25-year service lifetime total for both the PV panels + batteries
- Production 5,886 kWh/yr and autonomy 59.3 h.

HOMER models emissions only for generators, boilers and reformers. To identify the levels of emissions for this optimum solar PV + batteries set-up, annual power output results and data on typical levels of CO_2 emissions from solar PV panels were used. The NREL value [21] is 40 g CO_2 per kWh for solar PV. With 5,886 kWh produced annually, this gives 5,886 kWh x 0.040 kg = 235.44 kg CO_2 emitted.

From Table 5, it can be seen that solar PV + batteries set-up was the most favorable renewable energy system for the mobile AMS, with the lowest NPC (11,804 USD), LCOE (0.31 USD), and annual operating cost (178.26 USD), and rather low annual CO_2 emissions. The diesel-run generator exhibited the highest NPC value (32,141 USD) and the largest amount of annual CO_2 emissions (3,389 kg). Various perspectives (economic, environmental, uncertainty) considered when comparing and choosing between the renewable energy types are discussed below.

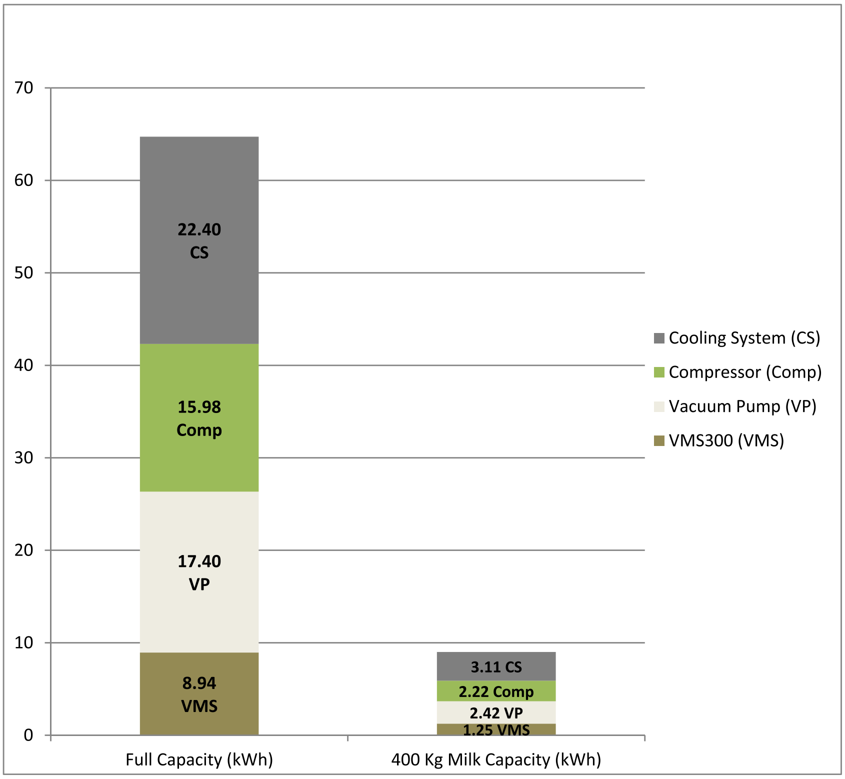

Figure 4. Energy consumption for the AMS facility with components when operating at (left) full capacity and (right) 400 kg milking capacity.

Table 5. Summary of HOMER simulation results.

Power Source	NPC (USD)	LCOE (USD)	Annual CO_2 emissions (kg)	Initial capital cost (USD)	Annual operating cost (USD)
Solar PV + batteries	11,804.00	0.31	235.44	9,500.00	178.26
Ethanol-run generator	26,115.00	0.62	1,344.00	2,580.00	1,821.00
Biodiesel-run generator	33,312.00	0.78	-33.60	2,580.00	2,377.00
Biogas-run generator	19,036.00	0.45	0.29	3,139.00	1,230.00
Diesel-run generator	32,141.00	0.76	3,389.00	2,580.00	2,287.00

3.1. Economic perspective

Solar PV + batteries had the lowest costs of all renewable energy candidates, with the lowest NPC and LCOE (Table 5). Moreover, although the initial capital cost was highest for the solar PV setup (9,500 USD), it had the lowest annual operating cost (only 178.26 USD), making it still the best choice from an economic long-term perspective. The biodiesel-run generator had the highest NPC (33,313 USD), LCOE (0.78 USD), and annual operating costs (2,377 USD), making it the least economically favorable renewable energy option.

The project life time of 25 years for the solar set-up was clearly economically better than the other possible time spans of 10, 15, and 20 years, for which NPC was 17,893, 14,409, and 12,844 USD, respectively, and LCOE was 0.47, 0.378, and 0.336 USD, respectively.

Although the choice of materials for all renewable energy types should be investigated further to reflect available options within Swedish markets, comparison “as is” from an economic perspective provided a similar outcome regardless of the choice of materials, which after all was a common feature of all renewable energy systems considered. This was reflected in simulation of a common discount rate (8.0%) and inflation rate (2.0%) for the costs, along with a range of project life times (10, 15, 20, and 25 years), to reflect the sensitivity of the variables used. Similar approaches have been used in previous modeling studies on how global biomass potential is influenced by different long-term development paths in the food and agriculture system, and on potential future biomass supply from plantations [for review, see 30]. Due to the projected imbalance between bioenergy supply potential and prospective bioenergy demand in the world, higher biofuel prices in the international market are expected in future [30]. According to the Swedish Energy Agency, the significance of the two previous studies lies in the fact that both are based on comprehensive data inventories and modeling, allowing for consistency over world regions [30]. Together, they illustrate the sensitivity of results to variations in key parameters [30].

The second best renewable energy option, the biogas-run generator, scored better than solar PV + batteries in terms of the initial capital cost. The potential for providing less expensive power to the mobile AMS with biogas is quite promising, provided that the biogas produced locally suits the AMS set-up.

Solar PV + batteries showed promising results, but future projections are needed on the technology and how it compares with Swedish grid-connected systems in terms of costs. A recent study exploring off-grid electricity production in Sweden conducted by the Royal Institute of Technology (KTH) Sweden provided valuable data to assess the solar PV set-ups [31]. Using HOMER Pro, the following four systems were modeled at two different locations in Sweden (Visby, Östersund) in that study: (i) Off-grid household comprising hydrogen tank + PV + battery energy storage system (BESS), (ii) partially off-grid prosumer household comprising PV + grid connection, (iii) partially off-grid prosumer (producer and consumer) household comprising PV + BESS + grid connection, and (iv) grid-connected household [31]. Table 6 shows LCOE for these four systems.

Comparing the LCOE values in Table 6 with those obtained for the best possible energy source for the mobile AMS in this study (0.31 USD/kWh or 2.74 SEK/kWh), it is obvious that all off-grid systems, including solar PV + batteries, were less economically favorable than the options considered in Table 6. Only the hydrogen + PV + BESS option was more expensive than off-grid systems in the present study. That study also provided future projections of LCOE in 2030 and 2040 (Table 7).

Based on the data for 2020, connecting the mobile AMS to a grid-connected system rather than a solar PV + batteries set-up would be more economically favorable. However, looking at the projected figures, the balance will eventually change in favor of the solar PV + batteries set-up, since network charges and energy taxes in grid-connected systems are likely to rise over the years, while the costs of PV panels, batteries and inverters are predicted to drop (by 20%, 50% and 20%, respectively) [31]. Rapid development in efficiencies and in the technology will also contribute [32].

3.2. Environmental impact

Biodiesel- and biogas-run generator types had the lowest levels of CO_2 emissions (0.29 kg and -33.60 kg), followed by the solar PV set-up (235.44 kg) and then ethanol- and diesel-run generators (1,344 kg and 3,389 kg, respectively). However, to maintain a safe and clean environment, extra care is needed in handling and storing all these fuels, which have flammable and polluting characteristics. From this perspective in particular, the solar PV set-up is a better choice. Besides producing very low levels of CO_2 emissions, it has also very low potential risks of site pollution from spills of fuels or physical contaminants. For instance, comparing the solar PV set-up with use of a diesel-run generator, more than 78 tonnes (3,389 kg × 25 years compared with 235.44 kg × 25 years) of CO_2 emissions could be avoided over the optimum 25-year project lifetime.

Another important factor to consider is noise pollution. Keeping noise levels low is important, since exceeding the threshold (85 dB) can cause negative behavioral responses in cows, and consequently affect the levels of milk produced and profits [33]. From this perspective, the solar PV set-up was again the best option, because it does not produce any noise. In fact, installation of solar panels was found to be a source of comfort in a recent study, by providing shade for the cows [34]. An excerpt from the University of Minnesota's study on the Northeast Organic Dairy Producers Alliance (NODPA) newsletter stated: "*Our study indicates that agrivoltaics may provide an acceptable method of heat abatement to pastured dairy cows, as well as generating electrical energy for farmers. This would reduce the carbon footprint of the dairy operation.*" [34].

The HOMER results indicated that a total of 16 PV panels (area of 31 m^2) would be required to meet the 9 kWh per day load. Installing such a large area of PV panels on top of the 30-foot AMS container (22.3 m^2) would be challenging. This is a drawback of the solar PV set-up compared with the other renewable energy sources considered. Biogas renewable energy was the second least favorable option, as it required storage space for the fuel used (i.e., cylinders in this case).

Installation practicalities and challenges could be addressed by redesigning the solar system altogether, perhaps by including higher-capacity panels (e.g., 400 W), or altering the placement of the solar panels and set-up (e.g., number of strings and subarrays). The worst-case scenario would be adding extra space to the container top (in this case 31 m^2 vs. 22.3 m^2 = additional 8.7 m^2). There are several options/orientations to install the panels: directly on top of the container with no tilt, or on top of an additional rooftop space made available by swinging the container sides upwards. The optimum installation requires further investigation.

In addition to the installation challenges, the environmental impacts of the solar PV set-up need to be recognized and addressed. A previous study on two PV modules found four main environmental impacts: dust accumulation, water drops, shading effects, and bird droppings (fouling), with the shading effect having the most negative impact on module performance [32]. With 75% shaded area, the reduction in short circuit current, open circuit voltage, and power output was 66.5%, 25.3%, and 92.6%, respectively [32]. Thus the solar PV system must be installed in an appropriate location for maximum efficiency and avoiding shading conditions, and regular cleaning of panels (once a week minimum) may be needed [32].

While choosing the right renewable energy source for the mobile AMS set-up is important, it is equally important to pay full attention to the AMS manufacturer's general recommendations. This can help reduce the overall O&M costs and ensure a cleaner and safer environment post-installation. According to the manufacturer DeLaval, there are strong connections between animal welfare, cow longevity, and energy-efficient farms. It makes two key recommendations [35]:

- Install the right pump, since a larger pump can consume up to 20% more energy than a smaller pump.
- Use a plate cooler, which can cut the refrigeration energy costs by up to 60%.

In order to reduce costs further, key materials such as the PV panels, batteries, and inverter must be chosen carefully and sourced locally. Although the design for the mobile AMS-RE set-up currently addresses only a small number of cows (n = 20), from a design perspective the plan should always be to accommodate larger numbers to meet future needs.

Water and feed are two vital inputs during milking, so sufficient quantities of these must be available on-site. When milking only 20 cows, the amounts required will not be very large and could be made available on-site on a daily basis. When milking more cows, direct access to water from a nearby facility would be necessary. Overall, there should be a balance between costs and adapting to site constraints and conditions.

Based on the results and the above considerations, the solar PV + batteries set-up would still be the most suitable off-grid system, although today in Sweden a grid-connected system would be more favorable from an economic perspective. This may soon change, considering future projections of increasing grid electricity prices, coinciding with technological advances and rapid cost decreases in renewable energy supply. According to Khalilpour, R. and Vassallo, A., from University of Sydney "leaving the grid" and "living off-grid" may eventually no longer be an ambition, but rather a "real choice" [36]. This will prompt public interest and excitement, and a "death spiral" for utility services, whose traditional customers will leave the grid to become prosumers (i.e. producers and consumers), leading to further increases in grid electricity prices for the fewer customers left sharing the network [36].

In the case of the mobile AMS and other innovations, solutions to challenges should never be confined to what new technologies or concepts have to offer. Success in entering the market lies beyond overcoming the technological barriers, and is associated with policies in place, development of the market and infrastructure, and uncertainties about actual environmental benefits. For future success of a mobile off-grid AMS, there is a need to address factors such as milking frequency,

Table 6. Levelized Cost Of Energy (LCOE, Swedish Krona) for four different systems modeled at Visby and Östersund, Sweden, for 2020 [31].

Location	Average LCOE (SEK/kWh)			
	Hydrogen + PV + BESS	PV + Grid	PV + Grid + BESS	Grid
Visby	12.33	0.86	0.93	1.94
Östersund	16.42	1.11	1.17	1.68

Table 7. Levelized Cost Of Energy (LCOE, Swedish Krona) for four different systems modeled at Visby and Östersund, Sweden, for 2030 & 2040 [31].

Location	Average LCOE (SEK/kWh)			
	Hydrogen + PV + BESS	PV + Grid	PV + Grid + BESS	Grid
Visby (2020)	12.33	0.86	0.93	1.94
Visby (2030)	5.78	0.84	0.85	2.94
Visby (2040)	4.33	1.05	1.02	4.04
Östersund (2020)	16.42	1.11	1.17	1.68
Östersund (2030)	7.55	1.23	1.21	2.55
Östersund (2040)	5.71	1.54	1.48	3.49

cow and grazing management, pollution of the surrounding environment, cattle welfare, etc.

3.3. Uncertainty

Prior to decision making on final design, it is crucial to assess the level of uncertainties within the data. For the possible energy sources compared here, some input parameters require further analysis to minimize the uncertainty. These include fuel costs (biofuel); climate conditions (e.g., solar irradiance); key component costs (e.g. generators, solar PV components); key component and fuel efficiencies; and O&M costs. Uncertainties in these parameters generate uncertainty within the techno-economic and environmental results obtained (i.e., NPC, LCOE, annual CO_2 emissions, initial capital costs, and annual operating costs). A study comparing HOMER results with results from another analytical model (Monte Carlo) showed that percentage differences within LCOE values between the two models were up to 10% due to an uncertainty in fuel costs alone [37].

4. Scalability and replicability

The global dairy sector is growing rapidly, with world milk production projected to increase by 177 million tonnes by 2025, at an average growth rate of 1.8% per annum from 2015 [38]. In parallel with this rapid growth, demand for sustainable dairy farming that combats climate change is growing worldwide. The proposed mobile milking facility may meet this demand, so it is relevant to consider key factors that may affect the scalability and replicability of the proposed set-up. Scalability is defined here as the ability of a system to change its scale in order to meet growing volume of demand [39], while replicability refers to successful performance of a system under different boundary conditions.

Four main factors influence the scalability and replicability of a project: technical, economic, and regulatory factors, and stakeholder acceptance [39]. In this study, no specific methodology was used to evaluate the scalability and replicability of the proposed solar PV-powered off-grid AMS. However, identifying what the four factors entail and considering the system components provided preliminary indications of barriers and limitations to scalability and replicability.

- *Technical factors*: These cover the compatibility of the new system with the technical environment in which it will be implemented and how the interactions between components of the system and the outside world are affected [38]. To assess the scalability within the technicality factor, the following features must be considered: modularity, technology evolution, and the nature of original existing infrastructure. To assess the replicability, standardization, interoperability (two or more components/system to interwork), and network configuration (i.e., external conditions) must be considered [39].
- *Economic factors*: A project will only be scaled up if it is viable on the intended scale (cost-wise and revenue-wise) [39]. These factors determine the extent to which the costs grow with a growing system. For replicability, the key features to be studied are macro-economic factors (profitability in other environments/countries), market design and business models.
- *Regulatory framework*: This defines the responsibilities and roles of stakeholders involved, rules and requirements to provide services, and means of regulating activities between all agents. In terms of scalability, regulations may impact the size and scope of the project [38]. Similarly, the replicability of a system or project may be affected either way by existing national or local regulations.
- *Stakeholder acceptance*: How ready stakeholders (policy/decision makers, end-users) are to embrace a larger project or system will determine the scalability. Stakeholder willingness to embrace a new idea/project will determine the replicability [39].

The proposed solar PV + batteries off-grid set-up will face possible barriers with regard to scalability from limitations in the existing infrastructure and modularity from a practical perspective. Adding more PV panels to meet a larger power load, due to an added AMS to meet larger number of cows to be milked (hence another attached housing/container to accommodate the AMS and the panels), might be possible. However, it would reduce the mobility of the set-up. One way of addressing the scalability issue would be to have another independent set-up running in parallel.

Technological evolution, especially the rapid development of PV panels in terms of efficiency, batteries in terms of storage capacity, and decreasing costs, provides greater scope for scalability. Regulatory framework factors and stakeholder acceptance for a scalable system are primarily linked to the success of the existing model, demand for a larger milking set-up, and how profitable and environment/animal friendly the larger system would be.

For the solar PV + batteries set-up, replicability may change when external conditions change. For instance, running the set-up in Sudan or Iraq, where the primary energy source (solar radiation) is abundant would certainly yield better results than running the set-up in Scandinavia. However, the economic affordability (at least at the initial phase) may be too high in lower-income countries. Depending on how the regulations are formulated and how profitable and beneficial the set-up would be for the end-users and stakeholders involved, the level of acceptance or resistance to the system will change. Future projections as ones shown in Tables 6 and 7 for the country/region in question would assist in assessing the replicability. One advantage that may play a major role in the replicability of the proposed set-up is the rapid development of solar technology at a reduced cost.

5. Conclusions

Within the given environment and with the anticipated levels of operation and operating period in this study, a solar PV + batteries set-up would be the best off-grid power source for a mobile AMS on pasture. The solar PV system fulfilled the key aspects of being environmentally friendly, cost-effective, and sustainable, with the lowest NPC (11,804 USD), LCOE (0.31 USD) and annual operating costs (178.26 USD) of all renewable energy types considered. Annual CO_2 emissions were also relatively low (235.44 kg). Initial capital cost was high (9,500 USD), but still acceptable since annual operating costs were low, at least in comparison with other renewable energy types. Sourcing materials locally and following the recommendations of the AMS manufacturer are also strongly recommended to reduce costs further and improve system efficiency.

One key concern with the solar PV setup lies in the limited available space to accommodate the recommended 16 PV panels. Using higher-capacity panels, re-structuring the array set-up, or adding more rooftop area to the container could be feasible solutions. Rapid development of solar technologies and associated PV panels, inverters, and batteries, and reduction in their costs over time, could be key drivers for an off-grid set-up. Although staying connected to the grid is currently more economically favorable in Sweden, future changes may tip the balance in favor of off-grid systems.

Developing a successful off-grid system for a mobile AMS will require close scrutiny of other factors, such as milking frequency, cow and grazing management, effects on the surrounding environment, effects on cattle welfare, and present and future regulatory policies, technologies and costs. This will result in creation of a resilient and environmental friendly off-grid mobile AMS facility.

Declarations

Author contribution statement

Musadag El Zein & Girma Gebresenbet: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

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