Upgradation of Khoa Production method in Manchar, India using Solar Powered System

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Abstract

India is one of the largest milk producers and converts 50-55% of the produce into milk products and sweets. One of the base milk products in Indian sweets in *Khoa*, which is traditionally produced locally in an open pan heated by burning firewood. This manuscript aims to replicate the *khoa* production facility of Mahesh Khawa Kendra (MKK) to simulate and cater the heat requirement of temperatures using solar thermal energy and replace the existing wood-fired boiler setup. The storage based evacuated tube solar collector model is simulated using MATLAB Simulink CARNOT Toolbox supported by designing procedure and critical assumptions. The simulation results performed are analyzed on monthly and annual basis and monitored through performance parameters like solar fraction, fractional energy savings, collector field efficiency, collector yield as well as utilizibility. The simulated results are promising to run the replicated system purely on solar energy with solar fraction of 1.06 of the annual operation and deliver average of 68% fractional energy savings.

Keywords: India, milk, khoa, solar, collector, fractional energy savings, solar fraction, utilizibility, CARNOT

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1. Introduction

The world milk production is projected to increase by 175 million tons (23%) by 2024 when compared to the base years (2012-14), the majority of which (75%) is anticipated to come from developing countries, especially from Asia (‘Dairy’, 2015). Besides higher profitability, traditional dairy products have acquired an interest in large-scale production to meet consumer demands (Velpula, 2018). India ranks first among the world’s milk producing nations since 1998 and has the largest bovine population in the world (*Solar Heat for Industry India*, 2020). About 50-55% of milk produced in India is converted into a variety of milk products through processes such as heat desiccation, heat acid coagulation and fermentation times (Velpula, 2018) .The thermal energy accounts for approximately 70% of the total energy needs in dairy value chains for processes like powering chilling and storage units, sterilization processes, spray drying, evaporation, pasteurization, and other processes (Greening the Indian Dairy Value Chain, 2019). Solar thermal systems can contribute enormously to driving various thermal processes in the dairy industry, which demand water temperatures at <120°C (*Solar Heat for Industry India*, 2020). Among all the milk-based products, this project focusses on Khoa. Khoa, one of the most important heat-desiccated products, is used as the base material for a large variety of sweet delicacies (Rasane, Beenu and Dey, 2015). About 600,000 metric tons of khoa is produced annually in Indian sub-continent, utilizing 7% of total milk production just in India (Rasane, Beenu and Dey, 2015).

1.1 Motivation

The first author of this manuscript likes to consume sweets on regular basis which led to curiosity in local sweetshop varieties and therefore, the local khoa manufacturing setups were explored near-by the city of Pune, Maharashtra India. In Manchar, three different khoa manufacturers were personally visited where firewood was the fuel to supply heat either to the khoa making pan directly or burning firewood to heat water, which in turn heats the milk using a steam/water jacket. The level of sophistication varied across manufacturers based on the investment made. Mahesh Khawa Kendra (MKK), located in Machar, Nashik Road, district Pune, is sophistically well equipped with wood-fired boiler and vertical open drum Scrap Surface Heat Exchanger (SSHE) machines for khoa manufacturing. The manufacturer openly discussed the ongoing problems regarding his woodfired boiler and related issues, and his willingness to shift to solar thermal technology as per feasibility. As a renewable energy

doi:10.18086/eurosun.2022.05.11 Available at http://proceedings.ises.org

enthusiast, personally, this was one of the big opportunities to work on an actual live project and potentially assess the transition of wood-fired boiler application to a partially or totally renewable energy-powered application. The core of this work is thus devoted to check the performance of a typical system and simulate the system components and based on the final performance, the design is finalized for khoa production process.

Fig. 1: Wood-fired boiler and firewood at Mahesh Khawa Kendra, Manchar, India (Source: Self-clicked) and Khoa making in-process in one of the khoa manufacturing machines (Source: Self-clicked)

2. Literature review

For finding relevant literature on the internet, renowned search engines, as well as scientific publishing literature platforms, were used, for example, Web of Science (*Web of Science*, no date), Scopus (*Scopus*, no date) and Google Scholar (*Google Scholar*, no date)along with the search portal provided by the University of Oldenburg, Orbis Plus (*ORBIS Plus Suchportal*, no date)

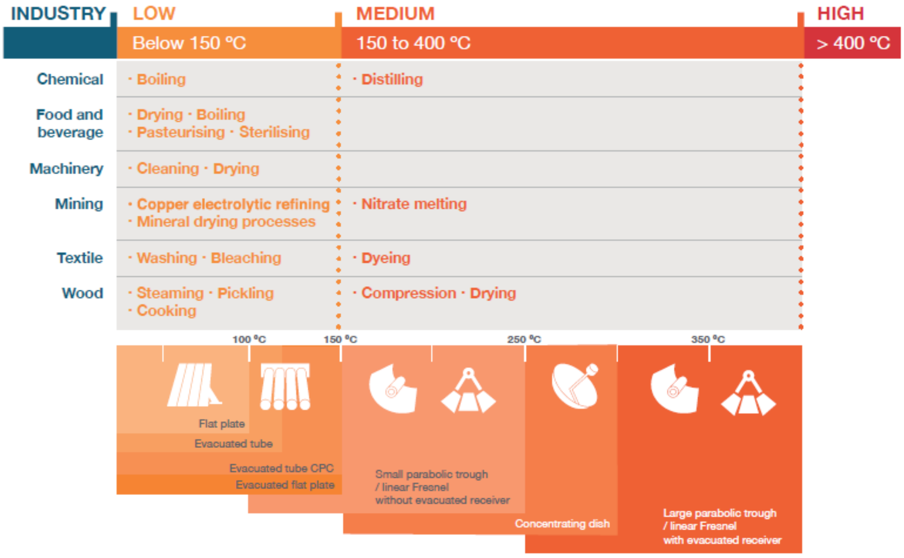
To segregate the results based on the target product to be produced, keywords like ‘Khoa’, ‘Khoya’, ‘Khawa’, ‘Khava’, ‘Khowa’, ‘Khova’, ‘Mawa’ were used to aim for literature for khoa production. To comply with the words used on the international level, additional keywords in the context of milk, like ‘desiccated’, ‘dehydrated’, ‘dehydration’, ‘condensation’, and ‘condensed’ were used as needed in sub-search options as needed. Not only these, the process of prolonged boiling milk to form khoa and the heat transfer processes involved were also included (for example, words like ‘heat’, ‘transfer’, ‘convective’).

2.1 Khoa

As per the Bureau of Indian Standards, IS:4883 (1980) states the definition of Khoa as followed: “KHOA (KHAVA, MAWA, and PALGHOA) refers to the milk product prepared by partial dehydration of milk by heating under controlled conditions” (BIS, 1980). It also states, “Buffalo’s milk is usually preferred over cow’s milk for KHOA production since the former gives greater yield and a more desirable body and texture”. As per M. Hickey (2009), “Condensed milk (plain) – is defined as obtained by partial removal of water from milk to which sugar may have been added” (Hickey, 2009). Concentrated semi-dried milk Khoa is produced by prolonged boiling of milk in shallow pans and drying it to a total solid amount of about 70 percent through a process of rapid evaporation of its water content (Nandi, 2009).

2.2 Khoa Production temperatures

Mahesh Kumar (Kumar *et al.*, 2011; Kumar, Prakash and Kasana, 2012), did extensive research through his studies for Khoa production including pool boiling of milk to assess khoa production temperatures. For his study, Kumar et al. considered the temperature range 90-95°C for nucleate boiling. Another team (More, no date) also developed a steam jacketed semi-mechanized Khoa-making equipment that maintained the temperature in the range of 60-120°C which varied across the drum length to control the quality and texture of khoa produced. Working in association with the local sweetmeat production units, it was ascertained that the operating temperature required for the preparation of Khoa is in the range of 95°C to 101°C (Nandi, 2009). To support the above-mentioned arguments, the Fig. 2 from the Solar Heat for Industry India (2020) report determines different solar collector technologies, temperature ranges as well as the applications for which the technologies are selected. Pasteurization and subsequent khoa production are considered in applications under 150°C. For temperatures specifically in the range 100-150°C evacuated collectors are considered.



INDUSTRY	LOW Below 150 °C	MEDIUM 150 to 400 °C	HIGH > 400 °C
Chemical	· Boiling	· Distilling	
Food and beverage	· Drying · Boiling · Pasteurising · Sterilising		
Machinery	· Cleaning · Drying		
Mining	· Copper electrolytic refining · Mineral drying processes	· Nitrate melting	
Textile	· Washing · Bleaching	· Dyeing	
Wood	· Steaming · Pickling · Cooking	· Compression · Drying	

Fig. 2: Selection of different solar collector technologies as per temperature range and application requirement (*Solar Heat for Industry India*, 2020)

2.3 Khoa production using Solar Thermal Energy

With relevance to solar thermal energy, Chaudhary and Yadav, (2020) conducted a study using an evacuated tube solar collector to power a simultaneous two-staged cooking system for cooking rice and khoa production. They observed temperatures in the range of 76 to 132°C with an average solar intensity of 857.96 W/m^2. The khoa was produced successfully with moisture removal of up to 73%. Nandi (2009) demonstrated khoa production using a parabolic concentrator system with 50% efficiency which would achieve temperatures for khoa production as well as other sweetmeats. Rao and team (Rao *et al.*, 2020) did a study on the economic analysis of khoa production in an open pan (kadhai) which used 60 kg of firewood to produce 11.5 kg of khoa using 40 liters of milk. Other papers were also available that dealt with economic analysis, but the specific fuel consumption was not mentioned. The paper from Rao et. al. can be referred to as one of the processes using firewood as fuel to produce khoa.

3. Methodology

The existing setup comprises a wood-fired boiler with helical water heating coil, flue gas-based water preheater, electric motor, two khoa manufacturing open drum-type SSHEs, pumps, and motors. The reason behind using specific firewood, *Acacia nilotica,* locally also known as *Babool/Babul treewood,* has the highest calorific value of 6130 kcal/kg (Chakradhari and Patel, 2016) or 25.6 MJ/kg. At MKK, mainly three products are manufactured namely Khoa, Basundi, and Pedha. Khoa being the most temperature intensive, high demand and with a long duration of cycle time (on full heat supply), it is being targeted for this application. Benchmarking was performed for the existing setup according to working hours, cycle times, operational pressures and assuming temperatures from the literature for khoa production, i.e., 105°C. These are crucial for feeding the data as per setup to the model.

To model the system, MATLAB Simulink was used with the help of the CARNOT toolbox as an add-on. The toolbox comes with existing models and blocks modelled with the help of S-functions and experimentally validated operational parameters presented in validation files which are available on the CARNOT database as well as in the help section (*Verification of Models - CARNOT Toolbox manual*, no date). However, all the data points mentioned by default in the existing models are not in-line with the khoa production system to be modelled. Meaningful connections, operational parameters as well as user-defined inputs (author's) were made to obtain fruitful results.

An important assumption here for load calculations is the milk is being treated as a fluid (liquid) throughout the khoa production process. It is necessary because CARNOT treats all the fluids in the connections as liquids. If at any certain point in the connection the gaseous phase (or water + steam) phase exists, the simulation would terminate. To understand the limitations of the tool to be used for simulations as well as to adhere to the heating temperatures as per the literature, the load calculations are performed by treating milk as an emulsion fluid. The khoa (milk fats) would be obtained simply by evaporation of water out of the emulsified mixture of milk. This is the reason the load calculations are not performed precisely based on energy demand as per products. Instead, the load calculations as per the load profile introduced will be calculated by CARNOT itself to eliminate any human ambiguity in the energy calculations.

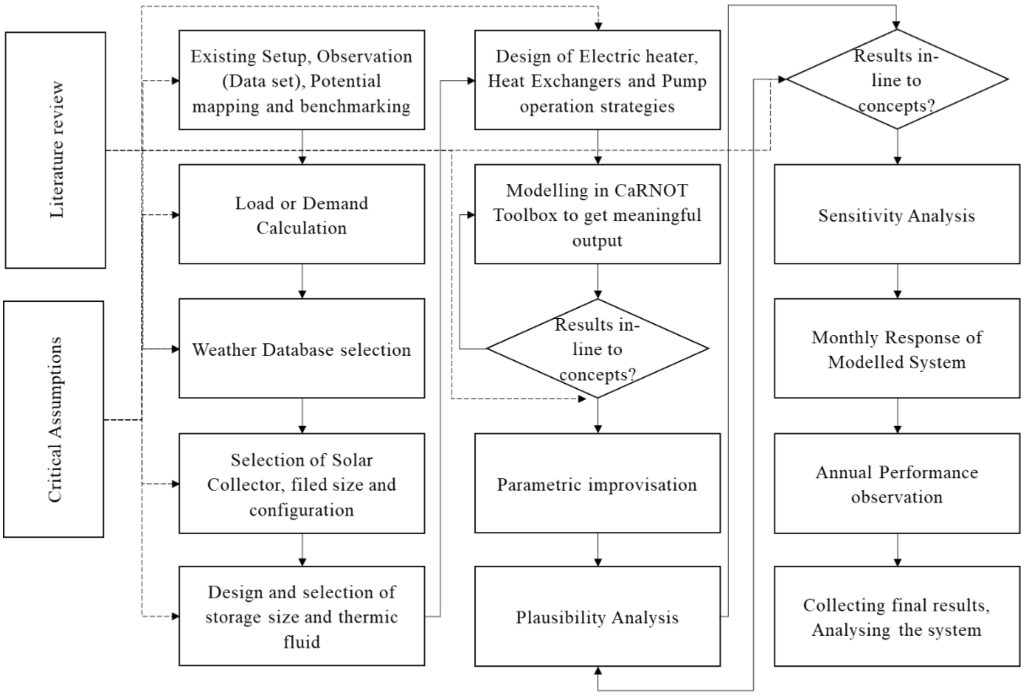


Fig. 3: Methodology flowchart of the steps for design procedure for the model supported by literature and critical assumptions (Source: Self derived)

Tab. 1: Load profile depicting the actual products used and the quantities

Parameter	Unit	Pasteurization	Khoa	Basundi	Pedha
Batches/vessel	40 liter Cans	9 (total)	5	2	2

The Weather Data Bus (WDB) in CARNOT processes the data in S-function and creates an input reference .mat file. Among all the datasets explored, the NREL NSRDB IDOC PSM v3 data (*NREL India Data*, no date) proved to be the most promising dataset available and averaged for 14 years from 2000 to 2014 and in line to the data demanded by the WDB. To avoid multiple changes in the tilt angle per year, JRC-PVGIS (*JRC PVGIS*, no date) suggests an optimum tilt angle that fits the best for seasonal variation. For the proposed system, although the location latitude is 18˚, the tilt angle suggested is 26˚. This has been fed to the WDB as well as in the model for solar collectors. The WDB averaged data also takes care of the seasonal variation in India with Summer, monsoons and winter roughly spanning across four months period each annually. To summarize, the WDB was fed for referring to the location coordinates of the khoa manufacturing facility (18.9828 N, 73.9446 W) with the optimized tilt angle of 26° facing to the south as provided from the JRC-PVGIS. The steps are summarized and represented in block diagram in Fig. 4.

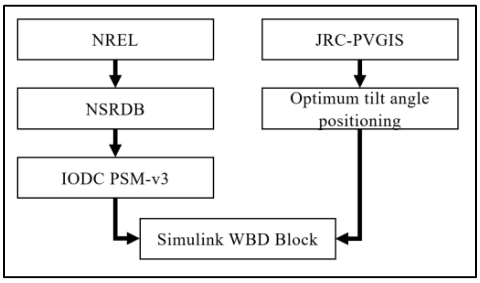


Fig. 4: Weather database source selection (Source: Self-derived)

For selection and adhering to the scientific details available for the collectors, evacuated tube solar collectors from Solflex (*Solflex Catalogue*, no date) make were used in this project. Before the solar collector field is sized, it is important to know how much solar radiation or solar energy is received at the location of MKK. This data was procured through an online portal developed by Solar GIS (*Solar Radiation Atlas*, no date), which could give a resolution of 10 km × 10 km. As per this source, MKK in Manchar receives GHI 1813.5 kWh/m^2/year. The sizing of the collector field is explained in Table 2.

Tab. 2: Calculations for collector field area and storage sizing

Parameter	**Unit**	**Value**	**Storage size selection multiplying factor**	**Volume (m^3)**
Annual demand	MWh/year	454.504		
Annual demand	kWh/year	454504.5		Selected as per Remmer (Torio, 2019)
Energy received at location (GHI)	kWh/year/m^2	1813.5		
Collector field area	m^2	250.62	As per Size (*150 lit)	37.59
Number of collectors	-	188.43		

As no guidelines are available for a storage-based khoa production system, the available literature for Domestic How Water (DHW) system was referred to and applied to the system design to simplify and justify the storage size selected. From guidelines provided by Remmer and Eicker (Torio, 2019) the storage size is parametrically obtained in liters as 150 times the collector field area calculated. The storage is assumed to lose heat/self-discharge only due to radiative losses from the side walls. This is supported by the assumption that the bottom of the standing cylindrical storage tank is in contact with the ground and zero radiative losses are expected from the base. And for the top of the cylindrical tank, it is assumed to have some air level at the top (not filling the tank completely). The dimensions of the tank are selected with a height to diameter ratio (H/D ratio) of a minimum of 2 to ensure enough stratification of hot and cold fluid inside the storage (Torio, 2019).

For effective heat transfer to take place on the primary and secondary sides, a heat transfer capacity of 505 W/K for each SSHE with 1.6 kg/s on the primary side and 0.069 kg/s on the secondary side resulted in effectiveness of 0.999 which is perfect for heat transfer. Accessorial components like load profiles for milk flow, water + glycol thermic fluid mixture, storage flow control in collector and khoa production loop were crucial for optimizing the flow to reduce unnecessary flow in components to reduce energy consumption, especially during non-sunny hours and night times. To get overview of all the steps followed in the methodology, please refer to the flowchart in Fig.3.

4. Results and discussions

For the system modelled, it is important for the components to align with the theoretical concepts to understand and meet the actual goals of the project. The plausibility analysis was performed, and the components behavior subjected to changing input conditions for a time scale of few days to two weeks depending on the component, temperatures achieved and on/off behavior as per load profiles. The simplified model is shown in Fig. 5.

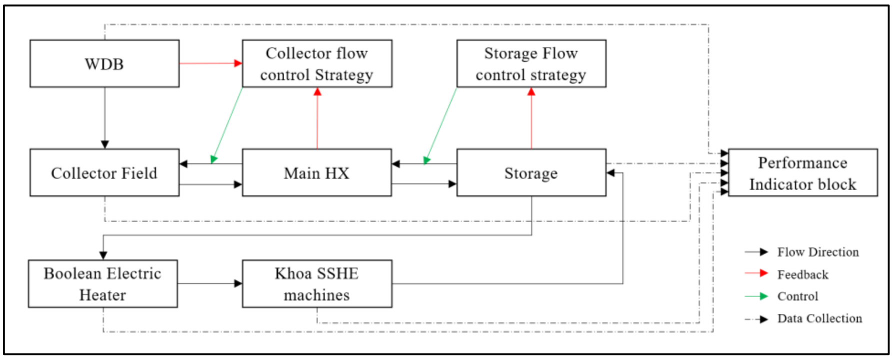


Fig. 5: Overview of the Simulink Model with components interacting among each other (Source: Self-derived)

The simulations performed were using sensitivity analysis as a tool to understand how the system is responding to the changes in system sizes as well as changes in input conditions. The response of the system is studied for a period of 60 days in such a way that on cold starting of the system, the storage can ramp up and achieve required delivery temperatures for khoa production systems at the end of the simulations. This is necessary to ensure that the errors would not be accumulating over different components and stacking up to a diverging trend for the entire system output.

Tab. 3: Components analyzed based on parameters changed and subsequent parameters for observing the component behavior

Component	Parameter changed	Analyzed using:
Collector field	• Field area (size) • Tilt angle • Mass flow rate	○ Cumulative Collector field energy
Storage	• Size	○ Cumulative Storage Energy ○ Instantaneous internal energy
Boolean Electric heater	• Storage size	○ Cumulative Electrical energy ○ Fractional energy savings
Khoa making process	• Milk input mass flow rate • Milk input temperature	○ Cumulative khoa energy ○ Khoa production temperature

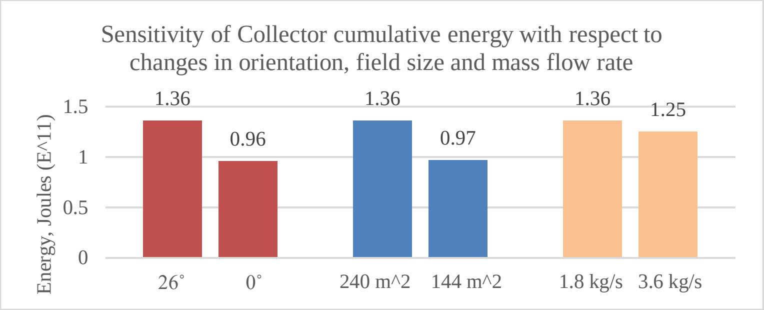


Fig. 6: Response in collector cumulative energy on different operating sizes and conditions represented sensitivity aspects

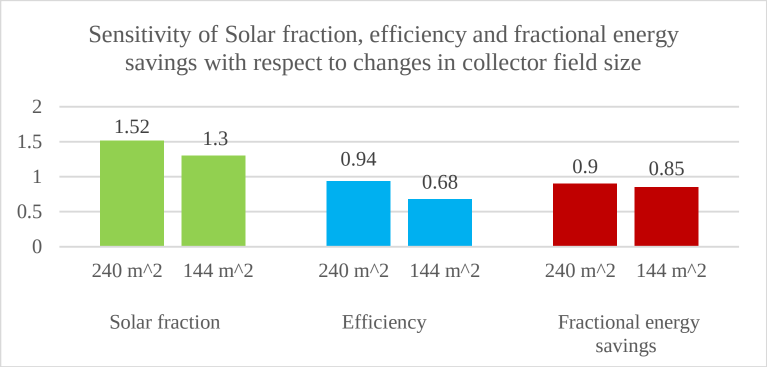


Fig. 7: Response of collector field to the performance parameters to change in field size

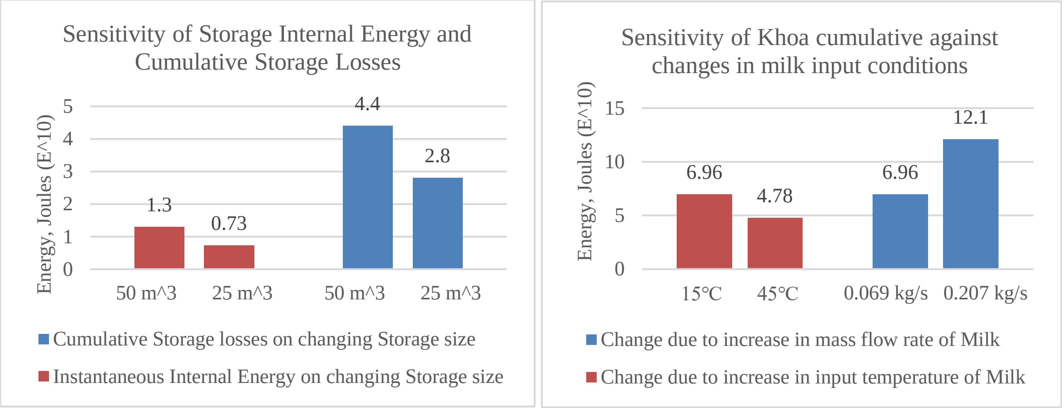


Fig. 8: Response of storage parameters on changing size and changes in khoa production energy on varying milk input conditions

Although the system sizing has been calculated using DHW as a starting point, the system size had to be optimized for the khoa production in such a way that the response of the system in terms of monthly and seasonal variation is better that the sized one as well as reconsidering the size of the system for economic investment if the real-time implementation is implements in future. The size reduction is a concern mainly for the size of storage as well as collector field. For the components used, different aspects had to be considered for performing the sensitivity analysis of the performance, which are specified in Table 3 and the changes in system sizes with respect to performance parameters are graphically depicted in Fig, 6, Fig. 7 and Fig. 8. The collector size was found 144 m^2 (reduced by 60% of design size) during the sensitivity analysis and simultaneously, as the storage size being dependent on collector field size, the optimized size is 22 m^3. Based on this, further performance analysis is proposed for the system using performance parameters.

4.1 Energy balance of the system

It is important to note that the energy balance is considered only using cumulative energy generated/consumed by the system across one operational year only. Ideally, it is expected to see the operation and balance for the long run (i.e., 3-4 years) but due to limitations of the tool to simulate and visualize properly for one operational year, the limit is up to one year only. Simulink was unable to compile the results for WDB for consecutive two years leading to the crashing of the entire MATLAB. Although thermally the heat transactions are expected to be the same at the start and end of the year, it is translated to the mathematical sum which should be ideally zero at the start and end of the year. The energies recorded by Simulink blocks on a cumulative basis are noted at the end of every year's simulation results to check the difference in the correct range. As it can be seen in Fig. 9, the heat sources are mentioned on the left-hand side and energies are flowing from the left to right direction. The energies considered here are irrespective of the signs (absorption or rejection) but are purely limited to consider only their magnitude. In an ideal case, the length of the bars on the left-hand side determined by the type of heat source must be equal to the final product expected on the right-hand side.

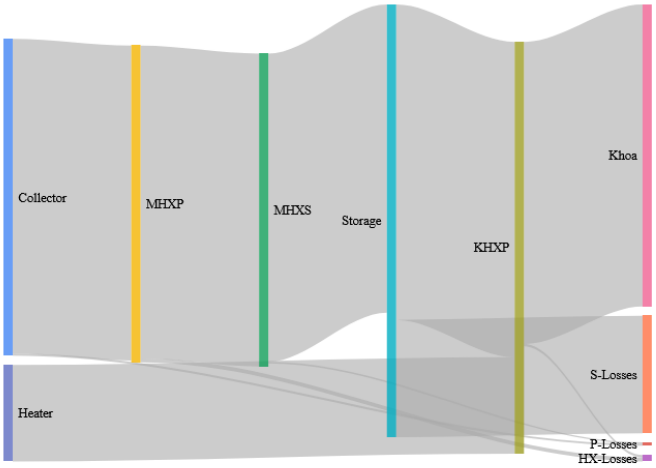


Fig. 9: Sankey diagram representing energy transfer among components for final system design (Source: Self Customized using JS Fiddle code)

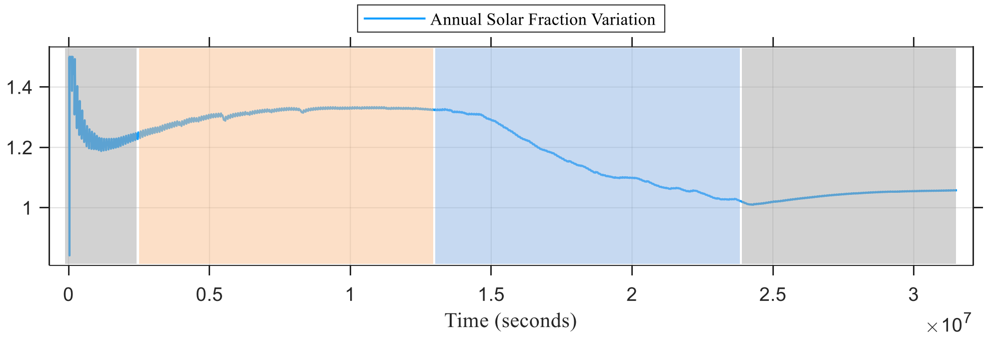
4.2 Evaluating the system performance using performance parameters

The performance parameters considered mainly are solar fraction, fractional energy savings, system efficiency, utilizability and collector yield. The solar fraction was mainly used for optimization for collector field and storage resizing and ultimately helping other performance parameters close by to justify the trade-off for a better, smaller system size with close performance. The fractional energy savings are considered against an identical system model with same input parameters, difference being a boiler with efficiency of 90%, electric heater with efficiency of 95% and a small storage of 10 m^3. Please refer to the graphs below in Fig. 11. Please take a note, the time series represented is in seconds, but separated for the seasonal variations as per color coding. Respective months of the seasons are discussed as per performance of the system for clarify for the reader.

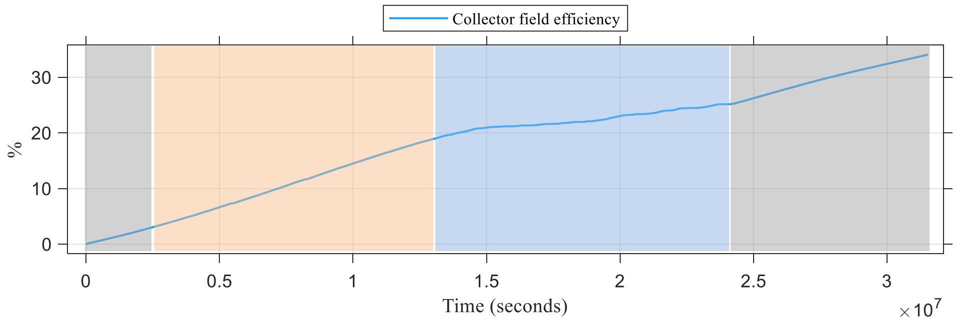
- The solar fraction at the end of the year: 1.05
- Solar collector field efficiency at end of the year: 34.1%
- System Utilizability: 820.5 kWh/m^2/yr

- Solar collector yield: 868.8 kWh/m^2/yr
- Fractional energy savings at the end of the year: 0.68
- Fractional energy savings average (with instantaneous behavior): 0.76
- Solar fraction Annual average (with instantaneous behavior): 1.18

🟧 Summer 🟦 Monsoon ⬜ Winter



(A)



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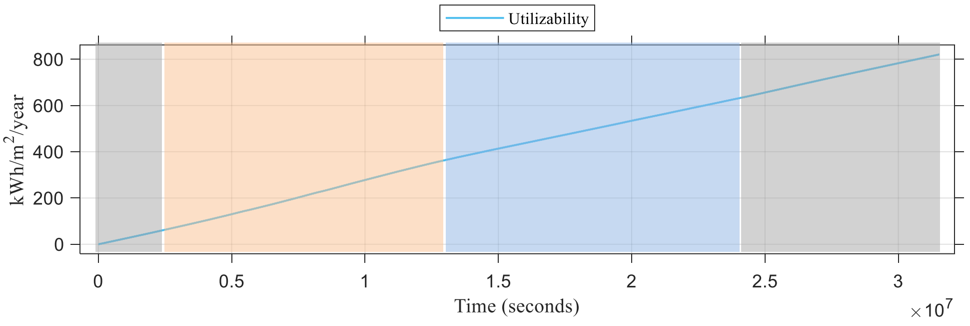

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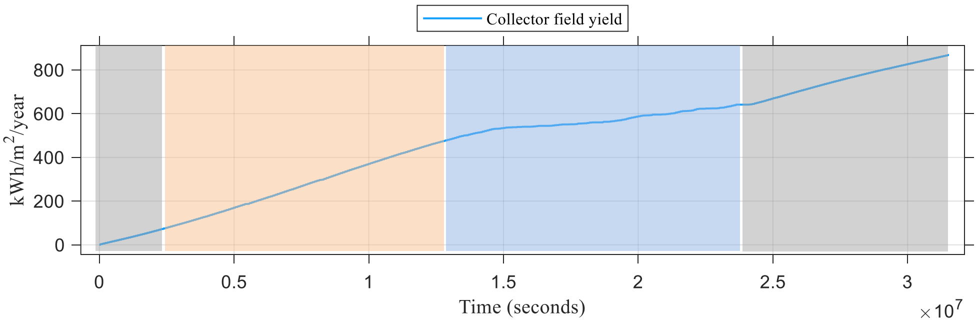
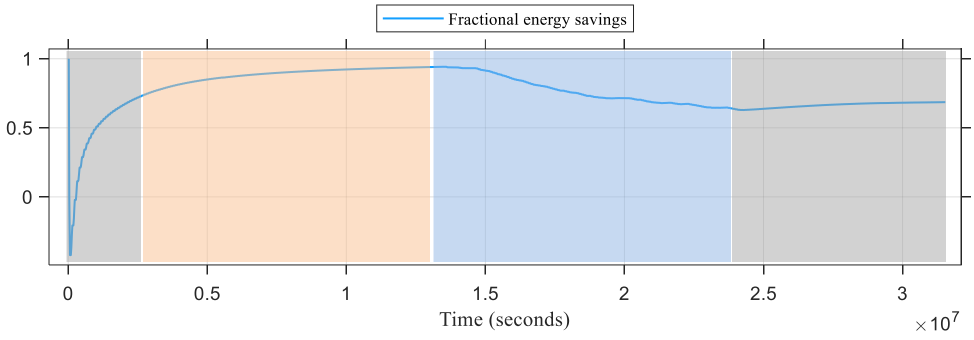


(D)



(E)

Fig. 11. Seasonal representation for explaining the share of solar energy in the khoa production system (A) Annual variation in solar fraction with values more than unity throughout the year (B) Collector field efficiency on cumulative basis(C) Utilizability and its trend with cumulative energies for calculation (D) Collector field yield with gradual decrease in slope for the monsoon season (E) Fractional energy savings against system's energy utilization from the heat source of solar collector field and Boolean electric heater

The seasons are represented as per time (seconds) namely March-May for summer, June-September for monsoons, and October to February for Winter. The graphs are to be seen one below the other and observe different parameters simultaneously as per season. As the system starts on the 1st of January, it is almost the peak of the Winter season and the energy requirements to ramp up the system are high. Although solar radiation is available, solar fraction drops down along with the fractional energy savings to charge the storage and gain energy. Gradually, as visible in Fig. 11 (E) the fractional energy savings are positive (after about 15 days) stating the system is now ramped up with the required temperature and actual benefits from the solar energy can be reaped. The participation of Boolean electrical heater (cumulative energy) stabilizes after this stage which reflects into fractional energy savings as well.

In the summer season, the system tries to run purely on solar energy which translates into minimum dependency on an electric heater and maximum savings (value approaching close to 1) as shown in Fig. 11 (E). For solar fraction, the system is approximately 130% efficient (as per system results, an error) and no dependence on external heat is observed. Logically and theoretically, it cannot be more than 100%, but can be supported with the statement of purely running on solar energy, without dependant on electric heater.

For the months of monsoon, the dependence on solar energy decreases as due to low available radiations, and simultaneously the cumulative Boolean electric heater energy increases due to low solar radiations and discharging storage energy, which reflects in Fig. 11 (A). The solar fraction decreases simultaneously reflecting into the increasing boolean electric energy, which in turn dips the fractional energy savings in Fig. 11(E). As the monsoon is over and the onset of winter, the solar radiations are back, but not with the same intensity as cumulative solar energy picks up and reflects onto the increasing trend of the solar fraction. This momentum is expected to continue and increase savings for the incoming summer season in the upcoming month and next year.

From the above discussions and inferences, it is clear that solar energy can play a majority role in powering the system thermally and reinforce the decision of running the khoa production system purely on solar energy. A boolean electric heater is an indispensable part of the system, but the maximum benefits are reaped using the designed collector field, storage as well as temperatures achieved and maintained in the system. This is in line with the expectations from the system in comparison to the traditional wood-fired boiler-powered system. The carbon savings achieved from solar energy as discussed in the upcoming chapter.

4.3 Emission savings using the proposed system

From the previous chapter, it is evident from the results and inferences drawn that the solar thermal system designed for khoa production can run on an average of 68% purely using solar energy. The remaining energy demands are catered to using electrical energy. The system, originally and currently running on wood fired boiler, can be run using solar energy and it can reinforce the objective of taking on this project initiative. As inferred in from the methodology chapter, the MKK uses Babul firewood. As per the literature survey conducted, there were no carbon sequestration reports available for babul firewood stating the exact emissions per kilogram of wood burnt or per kilo-Watt-hour energy produced. Instead, the IPCC guidelines (Freund *et al.*, no date) to choose carbon emissions in terms of CO_2 equivalent are used to calculate the annual CO_2 emissions from the MKK using babul firewood. If the solar thermal powered system is implemented assuming wood fired boiler as an auxiliary source of heat, the system would ideally save 68% of firewood consumed and replace it through purely solar energy. This is equivalent to 307.7 tonnes of CO_2 emitted every year saved.

But, as per the proposed system, the electrical energy is used to cater to the requirements of the khoa production system. Although the boolean electric heater is purely based on the temperature deficit-based operation system, for the calculation of carbon emissions, the electrical heater can be assumed to be operated using a fossil fuel-powered electrical grid. The carbon intensity of India's power sector is 725 grams of CO_2 per kilowatt hour (g CO_2/kWh), compared with a global average of 510 g CO_2/kWh ('India Energy Outlook', 2021).

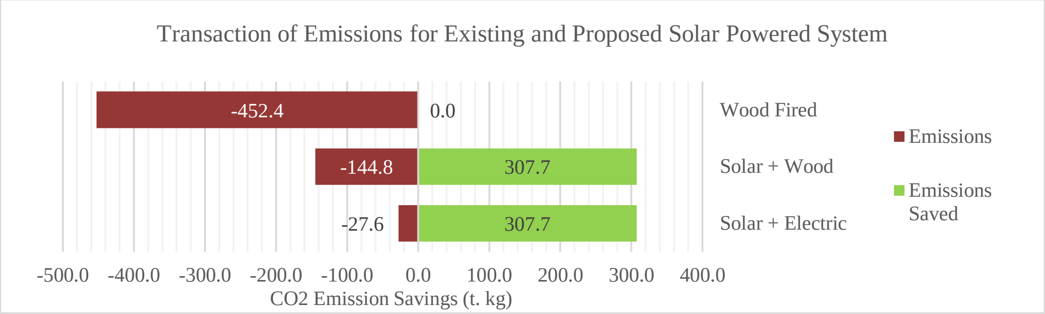


Fig. 12. Transaction for carbon emissions of existing and proposed solar powered system

It is quite evident that running the system with grid powered electrically heater-assisted solar thermal system is better than a wood-fired system and concretizes operationality as well as carbon savings of proposed system. It will be interesting to observe the system behaviour in the long run in-terms of solar fraction and fractional energy savings. The energy packages interacting in storage can be explored deeply along with minimizing dependency on electric heater. After all, the initiative to take up this project was to realize it on long-sustainable terms, the challenge is much bigger to learn during the process of implementation and pitch the product as 'green' khoa, with no/minimum emissions are involved in its production.

5. Conclusion

A genuine attempt was made to simulate an existing wood-fired khoa production system to work purely using solar thermal energy at Mahesh Khawa Kendra in Manchar, India. The system design is crucial in terms of the complexity of the processes involved and this being an attempt for a sophisticated yet novel system, the thumb rules for DHW systems proved to be helpful as a starting point. Although the system is slightly overdesigned in terms of the solar fraction of 1.06 for a simulation period limited up to one year period, the fractional energy savings achieved are satisfactory (68%) as compared to the existing wood-fired system in terms of emissions saved as well as partial dependence on the electrical heater. The overdesigning of the system is a result of diversion from the thumb rules considered and redefined for a khoa production system as per the demand assumed and results obtained for khoa production. The system highlights the dynamic behavior as per seasonal variation through numerous performance parameters, thanks to the reliable weather database file fed to the simulations. Plausibility analysis and sensitivity analysis proved to be important tools to explore component-by-component response and the performance of the system as a whole to exploit the performance as well optimize to a better sizing of the final system. After all, in comparison to the objectives of the project to simulate this system, the system performance is positive and promising to reduce the emissions significantly based on the firewood consumption and fractional energy savings on annual basis. The system is not perfect in terms of the expectations of shifting to 100% renewable energy, but the results are in a positive direction and capable to bring further insights with a better tool and a better approach. The technology simulated is promising and personally appealing to be extended further for implementation and gaining the confidence of the solar system manufacturers and dairy industry operators to head towards sustainable, green, emission-free dairy product manufacturing.

6. Acknowledgments

I would like to express my sincere gratitude to owners of Mahesh Khawa Kendra who gave the freedom to observe and improvise the existing setup, Dr. Herena Torio for guiding me regarding this project and my friends, family and critics who kept me pushing towards continuous improvement.

7. References

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