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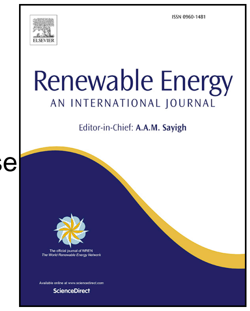


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# Optimal design of solar-assisted industrial processes considering heat pumping: case study of a dairy

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**Abstract**

Pinch analysis and Mixed Integer Linear Programming (MILP) have been extensively studied for optimization of industrial processes addressing heat recovery, utility selection and sizing. Analysis of renewable utility integration, such as solar thermal or photovoltaics, introduces several obstacles for established methods: the time-dependency of resources, storage inertia and losses, and intrinsic non-linearities of the system performance are difficult to represent by linearized, time-invariant MILP equations. Moreover, waste heat recovery options such as heat pumping cannot be neglected as a potential competitor to solar heat.

This work presents a set of multi-period MILP equations for solar technologies as well as a superstructure for optimization of heat pump cycles. Additionally, a methodology is proposed and applied to simultaneously optimize the process' refrigeration and renewable utility system using ε-constrained parametric optimization. The proposed methodology is illustrated on the basis of a dairy plant for which the different utility technologies are compared and evaluated based on economic and environmental criteria.

It is illustrated that integration of solar energy can contribute to strongly reduce the environmental impact of the process (65 - 75% reduction in $CO_2$ equivalent emissions), but only in combination with heat recovery (27%) and an improved heat pump system (33%). Heat recovery and heat pump placement for industrial processes are hereby shown to reduce exergy destruction and total cost while improving system energy efficiency by means of thermo-economic optimization. The solutions show that investment in solar energy can be economically and environmentally attractive for industrial processes by considering the whole system and ensuring that solar energy is optimally integrated and utilized.

*Keywords:* multi-period MILP, ε-constraint optimization, heat pump superstructure, flat plate thermal collectors, photovoltaics, thermal storage

## 1. Introduction

Within 90 minutes, enough solar radiation reaches Earth's surface to fulfill the total global primary energy demand of one year [1]. This illustrates the enormous potential related to solar energy which is virtually inexhaustible, abundant, and carbon-neutral if gray energy of the conversion equipment is disregarded. Photovoltaic and solar thermal collectors are widely employed and tested (for warm water, heating and electricity production) in the urban sector; however, application in the industrial sector is still scarce [2]. Although the potential has been extensively proven [3, 4], implementation of solar energy in industrial processes is constrained by several obstacles. Identification of the best point of integration is not trivial and should comply with the process specific thermodynamic and technical constraints related to e.g. the heat exchange equipment [5, 3].

One important point which is often neglected is that integration of more efficient or less emitting heating sources (such as solar thermal) should always be compared to other process optimization measures. Process

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