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# Process intensification and integration of solar heat generation in the Chinese condiment sector – A case study of a medium sized Beijing based factory

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A B S T R A C T

Over the last decade, energy prices in China have risen dramatically. At the same time, extensive use of coal fired energy provision systems in industry has led to serious environmental and economic problems translating to an economic damage of an estimated 10% of the Gross Domestic Product. This has led to increasing awareness in the process industries of the need to save energy whilst replacing conventional energy sources with renewable ones.

An energy audit was conducted for a soy sauce production facility in Beijing, which aimed to reduce its thermal energy demand through process intensification and to integrate renewable energy. Their current supply of thermal energy came directly from a district steam network, which was both directly consumed and downgraded via heat exchangers. It was determined that the best two solar integration locations would be in the pre-heating/mixing of raw ingredients to 60 °C and the subsequent direct steaming of the mixture to 120 °C.

Three different systems for supplementing steam were investigated: (1) a traditional solar thermal heating system; (2) a system consisting of mono crystalline photovoltaic panels coupled with either a resistance heater or electric steam generator; and (3) a cascading system consisting of two types of solar thermal collectors, photovoltaic panels, and an electric steam generator. Comparisons of systems 1 and 2 were made for the heating of mixing water, and systems 1, 2, and 3 for saturated steam generation.

Results showed that for the heating of process water, flat plate solar collectors performed best with an estimated 20 year Levelised Cost of Energy of 0.063 €/kW h. Steam generation was most cost effective with a cascade system of photovoltaic and flat plate collectors, with an estimated 20 year Levelised Cost of Energy of 0.145 €/kW h. The model predicts that integration of this technology would lead to a reduction of 14% in heating utility demand.



## 1. Introduction

In 2011 China was the largest energy user in the world with a total consumption of 12,275 million tons of oil equivalent (21% of the world's energy use). Due to its rapid economic growth, the energy use has increased by more than 150% in the last decade [1], which has increased pressure on energy production. China's industrial sector accounts for almost 50% of the Gross Domestic Product (GDP) and for around 70% of the country's energy use [2]. The industrial sectors contribute more than 82% to the overall national emissions [3].

Coal and oil account for 70% and 18% respectively of the total primary energy consumption. Renewable energy sources currently only deliver 6.7% in total, of which Hydroelectric covers 6% [4]. China's coal consumption, on the other hand, has increased by 200% in the past decade. The extensive use of coal, and in many cases very old technologies in the power plants and boiler houses,

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| CPC | compound parabolic collector |
| CNY | Chinese Yuan |
| DHI | diffuse horizontal irradiation |
| DNI | direct normal irradiation |
| DR | depreciation rate |
| EEM | energy efficiency measure |
| ETC | evacuated tube collector |
| F&D | Food and Drink |
| FPC | flat plate collector |
| FYP | National Economic and Social Development Five Year Plan |
| GDP | Gross Domestic Product |
| GHP | gross heat production |
| IAM | incident angle modifier |
| IEA | International Energy Agency |
| LCOE | Levelised Cost of Energy |
| NPV | Net Present Value |
| NREL | National Renewable Energy Laboratory |
| O&M | operation and maintenance |
| PTC | parabolic trough collector |
| PV | photovoltaic |
| SCU | standard coal unit |
| SD | system degradation rate |
| SME | small and medium-sized enterprise |
| ST | solar thermal |
| UO | unit operation |

*Symbols*

| | |
|---|---|
| $a_1$ | linear thermal loss coefficient (W/m$^2$ K) |
| $a_2$ | quadratic thermal loss coefficient (W/m$^2$ K$^2$) |
| $A$ | area (m$^2$) |
| Area | solar system surface area (m$^2$) |
| Cost | cost of the solar field |
| $c_p$ | specific heat capacity (kJ/kg K) |
| $d$ | day |
| $D$ | energy demand (kW h/day) |
| $h$ | hour |
| $H$ | solar irradiation (kW h/m$^2$ h) |
| $k$ | thermal conductivity (kW/m K) |
| $l$ | length (m) |
| $L$ | project lifetime (a) |
| $m$ | mass (kg) |
| $p$ | peak |
| $\dot{q}$ | heat transmission (kW/m$^2$) |
| $Q$ | energy demand (kW h) |
| $\dot{Q}$ | solar energy yield (kW h/h) |
| $r$ | radius (m) |
| RCU | relative cost per unit (%) |
| REC | relative energy consumption per unit (%) |
| RSS | Ratio Soy Sauce (%) |
| RV | Ratio Vinegar (%) |
| $s$ | thickness of layer (m) |
| $S$ | highest specific solar collector daily yield (kW h/m$^2$), i.e. "Good Solar Day" |
| SEC | Specific Total Energy Consumption ($t_{\text{coal,equ}}/t_{\text{product}}$) |
| SSD | Specific Steam Demand (t/t) |
| SWD | specific water demand ($\text{m}^3_{\text{water}}/\text{m}^3_{\text{product}}$) |
| $t$ | time (s) |
| $V$ | volume (m$^3$) |
| $W$ | moisture content (%) |
| $\bar{Y}$ | annual specific collector yield (kW h/m$^2$ a)) |
| Yield | annual energy yield for solar system (kW h/a) |
| $\Delta h_e$ | heat of evaporation (kJ/kg) |
| $\alpha$ | heat transfer coefficient (W/(m$^2$ K)) |
| $\lambda$ | thermal conductivity (W/(m K) |
| $\eta$ | efficiency |
| $\vartheta$ | temperature (°C) |
| $\rho$ | density (kg/m$^3$) |
| $\pi$ | ratio of a circle's circumference and diameter (3.14159) |
| $\varDelta$ | difference |
| $\theta$ | solar beam incident angle (°) |

*Subscripts*

| | |
|---|---|
| 1 | peak hot water demand |
| 2 | peak steam demand |
| $a$, amb | ambient |
| Area | panel area (m$^2$) |
| $b$ | bottom |
| conc | concrete |
| cond | condensation |
| dem | demand |
| $e$ | evaporation |
| equ | equivalent |
| ga | gas |
| gl | glass |
| $h$ | heating |
| in | inside |
| Ins | insulation |
| $l$ | loss |
| li | liquid |
| mix | mixture |
| $O$ | optical |
| out | outside |
| PV | photovoltaic |
| $r$ | recovery |
| $s$ | steel |
| sb | soy bran |
| so | solid |
| ss | soy sauce |
| st | steam |
| ST | solar thermal |
| sys | system |
| $t$ | direct and diffuse irradiation |
| $t$ | top |
| tr | transient |
| $v$ | vat |
| $w$ | water |
| wa | waste |
| wb | wheat bran |
| wg | wheat grain |
| wh | waste heat |

*Superscripts*

| | |
|---|---|
| PV | photovoltaic |
| ST | solar thermal |

has led to serious environmental and economic problems translating to an economic damage of an estimated 10% of the GDP [5]. The Chinese government has addressed this issue through the Renewable Energy Law, passed in February 2005 [6]. The Chinese government has been investing heavily in renewable energy, in an effort to lower China's dependence on coal. With 133 GW of renewable energy technologies installed, China had the largest renewable capacity in the world in 2011.