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Scale-up study of hybrid solar parabolic trough concentrators to reduce the emissions of CO_2 in a Mexican industry sector from now to 2030

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Abstract—This work aims to study and analyze the potential and impact on CO_2 avoided emissions from now to 2030, of scaling up an innovative hybrid solar technology to satisfy the energy demand of the Food and Beverage (F&B) industrial sector in Mexico. Positive and negative economic growth (including the recession caused by the COVID-19 pandemic) is considered as well as three technological scenarios: large, medium, and short technology deployment (BTD, MTD, and LTD). The study is based on a top-down and a button-up approach to determine F&B sector final energy consumption growth and share of primary and secondary energy sources. The results show that the proposed LCPV/T technology has an excellent decarbonization potential in the studied sector, achieving GHG emissions reduction of up to 51.7% and 34.10% from the levels of 2018 for the negative and positive economic growth, respectively.

Keywords— solar hybrid, LCPV/T, industry, prospective analysis, Mexico.

I. INTRODUCTION

Worldwide energy demand continues to increase at a constant pace. In 2018, 81% of the world's energy was produced by fossil fuels, and by 2040 the worldwide final energy consumption will increase by 48% [1]. The excessive use of technologies that employ fossil fuels to satisfy the energy requirements of a more demanding population has increased the emissions of CO_2 to dangerous levels in the world during the last years. Thus, there is an urgent need to deploy renewables technologies on a large scale in order to revert this trend, especially in developing countries like Mexico.

In Mexico, the industry is the second-largest final energy consumer sector just after transportation, accounting for almost 32% of the final energy demand. 64% of the final energy demand in the Mexican industry corresponds to the consumption of fossil fuels to generate heat. About 30% of this heat demand is consumed at temperatures below 150°C to drive processes like boiling, pasteurization, drying, cleaning, sterilization, among others. This temperature can be efficiently produced by solar thermal collectors.

Photovoltaic/thermal solar collectors (PV/T) are capable of simultaneously producing heat and electricity. This technology allows us to have a more efficient conversion of the available solar resource, by recovering the heat that is not produced into electricity by the photovoltaic cells. Commercially available PV/T collectors generally consist of a photovoltaic panel that has a duct or piping array in the back to recover the heat with the flow of water or air. Nevertheless, the heat temperature reaches a maximum of 50°C, which is useful mainly for residential applications. Low concentrating photovoltaics and thermal collectors (LCPV/T), is a technology usually based in low concentrating geometries, like a parabolic trough that can generate heat at higher temperature levels in comparison with PV/T technologies. The LCPVT collector proposed in this study is a self-developed technology which consists of a triangular duct located in the focal point of the linear parabola. The duct has monocrystalline solar cells attached to the sides that receive concentrated solar radiation. Heat is recovered by water that flows inside the duct. This LCPV/T collector is able to produce water at 70°C, maintaining an efficient production of electricity.

The food & beverage (F&B) industry is one of the sectors with the greatest potential to incorporate solar-thermal and hence LCPV/T technologies, mainly due to the low-temperature processes involved in manufacturing. In Mexico, this sector accounts for nearly 5% of the industrial final energy consumption, where 78.2% accounts for thermal energy that mainly comes from fossil fuels, which combustion produces greenhouse gas emissions.

In 2015, Mexico emitted 683 million tons (Mt) of CO_2e, which is nearly 1% of the global CO_2 emissions. The manufacturing industry accounts for 9.3% of the national Greenhouse gas (GHG) emissions. The F&B sector emitted 1.64 Mt of CO_2e during the same year. For the Paris

Agreement, Mexico committed to reducing 22% the GHG emissions by 2030 compared to those issued in the year 2000 (about 530 Mt CO_2). This target includes sectorial detail, where one of the pledges is to reduce 5% of the GHG in the industrial sector by 2030.

Many studies presented in the literature deals with a prospective analysis of different strategies to reduce energy demand or to clean the energy matrix and hence reducing GHG emissions. These studies mainly focus on developing countries due to the increase in energy demand provoke by industrial development. Some of the technologies that have been studied are solar water heating [2], clean power generation technologies (Photovoltaics, Concentrated solar power, wind, nuclear, geothermal) [3–6], energy efficiency [7], and the deployment of innovative technologies [8], like the one studied in this document. In a similar context, this research presents a prospective analysis of the impact in the reduction of GHG emissions that the deployment of LCPV/T technology may achieve in the F&B sector in Mexico from now to 2030. The novelty of this work is related to determining the GHG emissions abatement potential of an innovative hybrid solar technology that could be an alternative for clean heat and power generation in the F&B sector in Mexico. The study is aimed to encourage further efforts in the development, enhancement, and application of hybrid solar technologies to decarbonize different industrial sectors in developing countries.

II. Methodology and Data

The study consists of a top-down complemented by a bottom-up approach to compensate for the lack of data required for a bottom-up detailed analysis. The top-down approach was used to analyze the historical relationship between the F&B sector final energy demand, and the exogenous variable (Gross domestic product), to finally determine the correlation between both variables. To determine the energy intensity of the sector and the participation of different energy sources (Natural gas, diesel, fuel oil, LPG, electricity), the bottom-up approach was utilized, where the historical share and participation of different energy sources in the energy mix was first analyzed.

The research starts with a historical analysis of the energy demand, fuel intensity, and the gross domestic product of the sector in Mexico. This allows determining the correlation between the economic development and sectorial final energy demand, as well as establishing the economic and technological scenarios to study. GDP was selected as the exogenous variable to correlate with the final energy demand, this macroeconomic variable has been widely used in the literature to predict the final energy demand of different countries [2,4,9]. A single regression analysis was performed to determine the correlation between the final energy demand of the F&B sector in Mexico and the GDP, where 29 observation points were considered (1990-2018). The objective is to determine a mathematical relation between the previously mentioned variables, that is used in the prospective software to calculate the final energy demand of the sector.

The GDP in Mexico has been increasing an average of 2.68% per year (Fig. 1). Nevertheless, according to nationally available data, the Mexican economy presented stagnation in 2019, which means no economic growth.

According to the available and reported data in Mexico, the food and beverage industry corresponds to the production of beer, soft drinks, ice, and tobacco. In 2018, 94.5% of the heat demand was produced by fossil fuels.

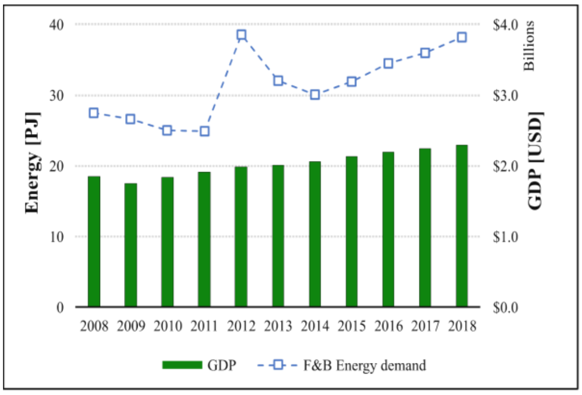

Fig. 1 Historical F&B energy demand and GDP of Mexico (Source: Own elaboration with [9]).

The historical fuel share in the final energy demand of the F&B sector is presented in Fig. 2. Electricity and Natural Gas (NG) share have increased during the last decade. In contrast, the Fuel Oil (FO) share has almost been eradicated since 2017. Moreover, Fuel oil has almost no presence in the F&B sector energy matrix. In the current accounts set up, 78% of the final energy demand is consumed in the form of heat in the sector. Natural gas and Diesel are the most consumed fossil fuels for heat generation, Fig 3. It is important to point out the absence of renewable energy sources in the energy matrix of F&B sector.

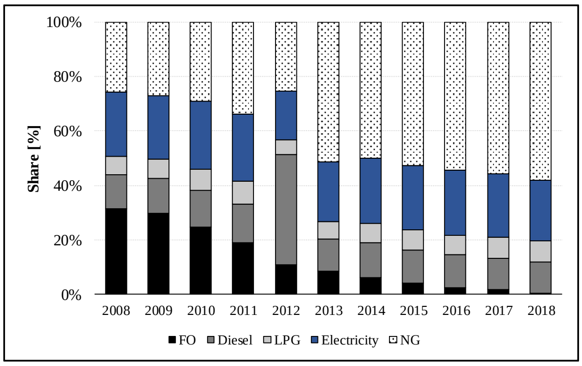

Fig. 2 Historical F&B share of fuels in Mexico. (Source: Own elaboration with [9])

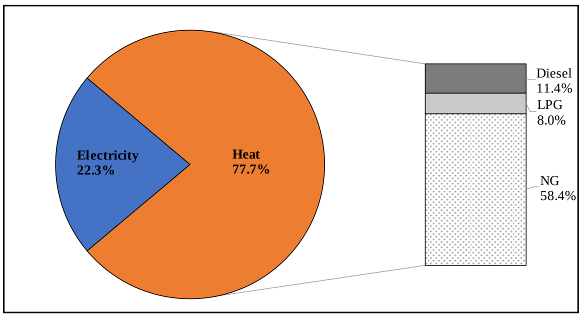

Fig. 3 Current accounts (2018) energy matrix of F&B sector (Source: Own elaboration with [9]).

A. Scenarios

The scenarios analyzed in this study were established considering two approaches. The first one is related to the economic growth of Mexico and the second one considers the level of deployment of the hybrid LCPV/T technology. Positive and negative economic growth scenarios were established with an annual growth rate of the GDP of positive 2% and negative 2%, respectively, from 2023 to 2030. From 2020 until 2022 the economic recession caused by COVID-19 pandemic was considered. The annual growth rate for the GDP of each economic scenario is presented in Table I.

Three technological scenarios were established, Business as usual (BAU), Medium technology deployment (MTD), and Large technology deployment (LTD). The first one is characterized by the increase in the share of Natural Gas and Electricity and slow penetration of solar technologies, which is a trend that can be observed in the historical share of fuels of the sector. Table II presents the annual growth rate of the share of every fuel for each technological scenario. In the MTD and LTD scenarios, LCPV/T participation in thermal energy demand is considered to achieve 11% and 28% respectively, displacing the share of NG, LPG, Diesel, and Fuel Oil.

TABLE I. ECONOMIC SCENARIOS GDP ANNUAL GROWTH RATE

Scenario	2019	2020	2021	2022	2023 - 2030
Negative	0%	-6%	-3%	0%	-2%
Positive					+2%

TABLE II. TECHNOLOGY DEPLOYMENT SCENARIOS SHARE ANNUAL GROWTH RATE

Source	BAU	MTD	LTD
Electricity	+ 2.68%	+ 2.68%	+ 2.68%
Natural Gas	+ 1%	Remain	Remain
Diesel	-10%	-10%	-10%
LPG	Remain	-10%	-10%
Fuel Oil	-10%	-21.5%	- 21.5%
Solar	Interp (2030, 0.5%)	Interp (2030, 7.8%)	Interp (2030, 19.5%)

B. LEAP model

LEAP (Long-range energy alternatives planning) software was selected to model the final energy demand and the GHG emissions of the sector. LEAP is an integrated software tool used to perform energy policy analysis, which is widely used for energy policy planning, climate change assessment, and cost analysis in a defined period. It is done by designing alternative scenarios, where each one has its specific information. All these characteristics allow developing a demand energy analysis based on demographic and macroeconomic data of the study area, like the gross domestic product, and calculate the emissions of GHG of established sectors.

The energy demand ($D_{b,s,t}$) is calculated as the product of the total activity level ($AL_{b,s,t}$) and energy intensity ($EI_{b,s,t}$) at each given technology branch (b), scenario (s), and time (t), eq. 1. Energy demand is calculated for the current accounts year and future years in each scenario. Current accounts are the starting data for all scenarios, and in this study, it corresponds to the year 2018.

$$D_{b,s,t} = AL_{b,s,t}\, EI_{b,s,t} \quad (1)$$

For the analysis of atmospheric polluting (PE), the emissions are calculated per consumed energy unit for each fuel source, this is based on the Technology and Environmental Database (TED). TED includes polluting emission factors ($EF_{f,v,y}$) proposed by the IPCC (Intergovernmental Panel on Climate Change), where the polluting emissions are classified by default in a hierarchical form according to the energy demand, eq. 2.

$$PE = \sum D_{b,s,t}\, EF_{f,v,y} \quad (2)$$

Finally, eq. 3 was employed to calculate the rate of change (RC) of the GHG emissions as a function of the F&B energy intensity of the sector for each technological scenario.

$$RC = {(PE_{s,i+1} - PE_{s,i})}\Big/{(EI_{s,i+1} - EI_{s,i})} \quad (3)$$

III. RESULTS AND DISCUSSION

The linear regression analysis results with a significant regression equation for the F&B sector energy intensity (EI) with a coefficient of determination (R^2) of 90.68%. The equation is presented in eq. 4, where GDP corresponds to the gross domestic product in a determined year in millions of US dollars. This correlation allows us to determine the F&B energy intensity as a function of the GDP for the years considered in this study.

$$EI[PJ] = 0.87 + 0.00001512(GDP) \quad (4)$$

From 2018 to 2020, the final energy demand of the F&B sector remains equal for positive and negative economic growth scenario, due to the equivalent GDP growth rates established for the first three years of the study. In the negative GDP growth scenario, in 2030, the energy demand of the F&B sector will be down to 29.27 PJ in comparison with 37.48 PJ in 2018, which corresponds to a 21.9% decrease. In the positive growth scenario, in 2030, the final energy demand of the sector will increase to 39.98 PJ, 6.7% percent more in comparison with 2018, Fig 4.

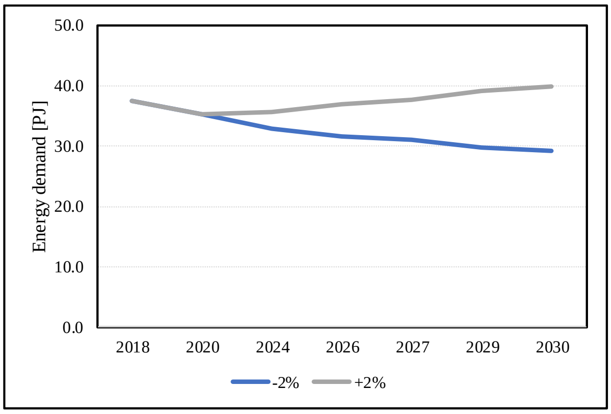

Fig. 4 F&B sector energy demand projection to 2030.

In Fig. 5, the evolution of the share of every fuel in the final energy demand of the F&B sector is presented for the year 2025, and 2030. It can be noticed that the heat generated by LCPVT technology displaces Natural gas, Fuel Oil, LPG, and Diesel in the MTD and LTD scenarios. Similarly, the electricity produced by the hybrid technology displaces the electricity produced by conventional technologies. Conversely, in the BAU scenario, Natural gas and electricity became the principal energy sources of the sector in 2030, with a participation of 65.5% and 30.3%, respectively.

The energy demand projection in 2030 for the medium technology deployment scenario results in a 9.35% participation of the LCPV/T technology. 5.2% of the electricity demand will be covered by the hybrid collectors as well as 11.2% of the heat consumption of the F&B sector. For the LTD scenario, 22.36% of the final energy demand of the sector could be provided by the LCPV/T solar technology. 12.8% of the electricity consumption and 28% of the heat demand could be produced by the proposed technology.

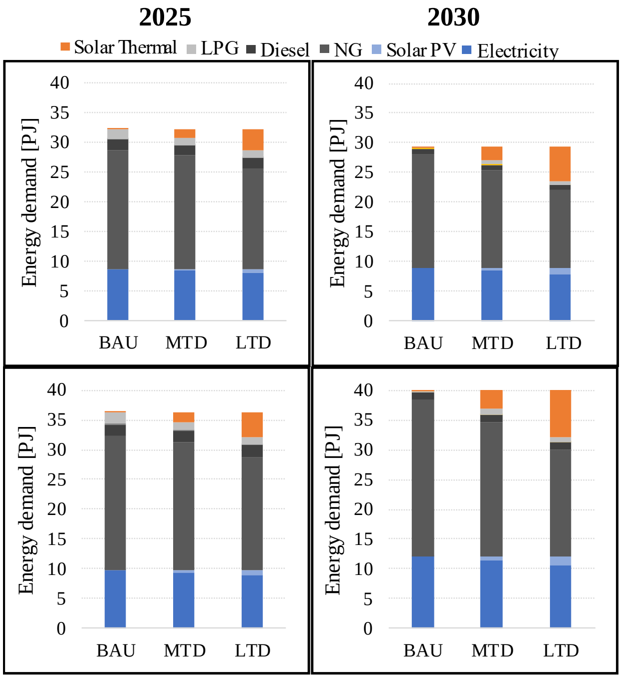

Fig. 5 F&B sector energy demand and share of fuels in 2025 (left), and 2030 (right) for negative economic growth scenario (up), and for positive economic growth scenario (down).

Regarding the analysis of the impact on direct GHG emissions at the point where emissions are produced, the F&B sector emitted 1.76 Mt of CO_2 equivalent in 2018. For the BAU scenario, 1.15 and 1.58 Mt of CO_2 will be emitted in 2030 for the negative and positive economic growth scenarios, respectively. This can be noticed in Fig 6. and Fig. 7. For the negative economic growth scenario, this corresponds to a decrease of 34.7% in comparison with the emissions of 2018. Nevertheless, this reduction is achieved by a decrease in the final energy demand of the sector. For the positive GDP growth scenario, a decrease of 10.2% in GHG emissions in comparison with 2018 is achieved, despite the increase in final energy demand of the sector. The reduction is due to the economic recession of 2020, the transition from Diesel, and LPG to Natural gas for heat generation, and an increase in electricity consumption due to the electrification of processes.

For the MTD scenario, the GHG emissions levels could achieve 1.04 and 1.43 Mt of CO_2 equivalent in the negative and positive economic growth scenarios in 2030, respectively. In the negative GDP growth scenario, a reduction of 40.91% in GHG emissions from the levels presented in 2018 is observed. Similarly to the BAU scenario, this decrease mainly comes from the reduction in the final energy demand, complemented by a displacement of Diesel, LPG and Natural gas produced by the generation of heat from LCPV/T technology. For the positive GDP growth scenario, the emissions in the MTD scenario decrease by 18.75% in comparison with 2018. The emissions reduction, apart from the transition to natural gas and electricity, is driven by a clean supply of 11.2% of the heat demand with the hybrid solar technology.

As it was expected, the LTD scenario, which considers the largest share of deployment of the LCPV/T technology, achieved the highest GHG emissions reduction by 2030. The pollutant emissions reach 0.85 and 1.16 Mt of CO_2e in the negative and positive economic growth scenarios. This corresponds to a decline of 51.7% and 34.10% from the levels of 2018 for the negative and positive economic growth, respectively. Additional to the decrease in energy demand in the negative economic growth scenario, the participation of the LCPV/T technology in the generation of 28% of the heat demand allows cutting by 2030 the GHG emissions to almost half of the ones presented in 2018. Whilst for the positive growth scenario, the generation of 7.78 PJ of thermal energy with the proposed technology accomplishes a reduction of 0.6 Mt of CO_2e by 2030.

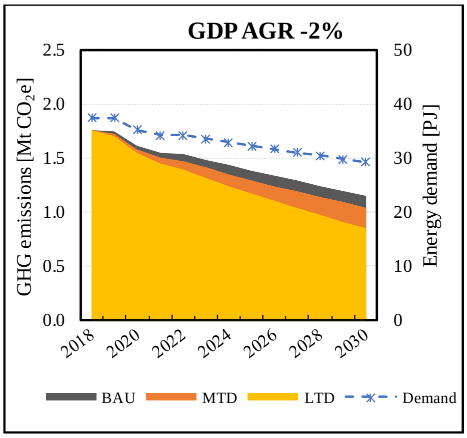

Fig. 6 2030 F&B sector direct GHG emissions (at point of emissions) for negative economic growth scenario.

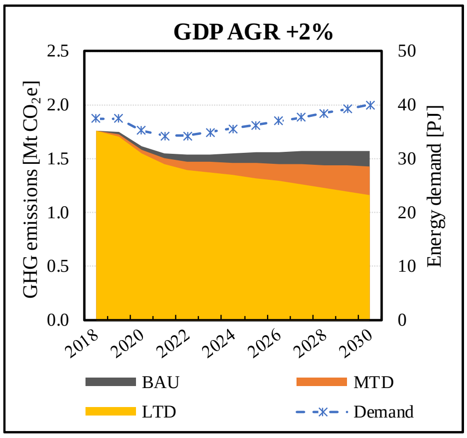

Fig. 7 2030 F&B sector direct GHG emissions (at point of emissions) for positive economic growth scenario.

One important finding of this study can be observed in Fig. 8. For the MTD and LTD scenarios, a decoupling of the GHG emissions from the energy demand profile is achieved, which is a desirable behavior that is presented in developed countries' industrial sectors. The rate of change of GHG emissions in the MTD and LTD scenarios reaches -10.17 thousand metric tons of CO_2e per PJ (Tt CO_2e/PJ) and -43.83 Tt CO_2e/PJ, respectively in 2030. In contrast within the BAU Scenario, after the economic recession, GHG emissions continue to rise as the energy demand increases at a rate of 2.68 Tt CO_2e in 2030. Nevertheless, the rate of change in the BAU scenario presents an average annual decrease of 19.33% since 2023, which will end up in a negative rate of change in the early next years. This behavior is attributed to the growth in participation in the energy matrix of natural gas and electricity (electrification of processes).

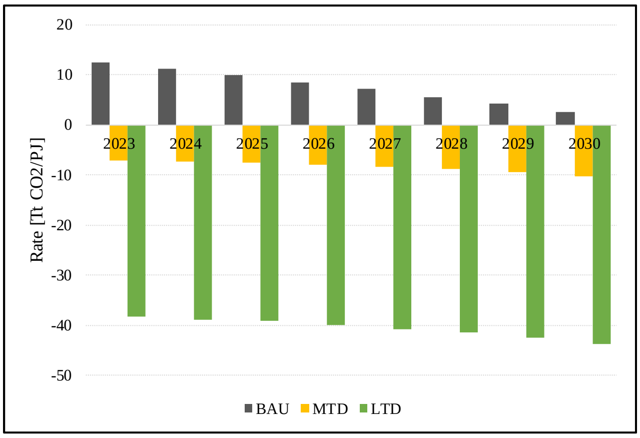

Fig. 8 2030 F&B sector rate of change of GHG emissions projection.

IV. Conclusions

The conclusions that we can share about the study are:

- In 2030 the energy demand in the Food and beverage sector could be 29.27 PJ and 39.98 PJ for the negative a positive economic growth, respectively.
- Heat demand will decrease from 78% in 2018 to 69% in 2030 due to the electrification of processes trends in the sector. LCPV/T technology could produce 23.36% of the final energy demand in the LTD scenario, 1.56 PJ of electricity, and 7.78 PJ heat.
- In the Medium technology deployment scenario, 9.35% of the final energy demand is generated with LCPV/T collectors, 1.14 PJ of electricity, and 5.70 PJ of heat.
- Electricity and Natural gas share in the final energy demand, continue to increase, in contrast with Diesel, LPG, and Fuel Oil, whose share decrease in all scenarios.
- Due to the COVID-19 recession, all scenarios (economic and technological) achieved a reduction in greenhouse gas emissions in comparison with 2018. Business as usual scenario is the only one that presented an increasing GHG emission profile post-recession.
- MTD and LTD scenarios can reduce greenhouse emissions by 18.8% and 34.1%, respectively, in comparison to 2018 emissions.
- Decoupling of the energy consumption and greenhouse gas emissions profile is achieved by MTD and LTD scenarios. Being LTD the one that presented the higher rate of change of GHG emissions per unit of energy.
- The proposed LCPV/T technology could support the decarbonization of the F&B sector in Mexico. Nevertheless, the deployment of this technology should be complemented by other energy sufficiency and energy efficiency alternatives, as well as renewable energy technologies, to achieve a higher impact on GHG emissions reduction.

The study should be further extended to validate the LCPV/T production considering the available solar resource, available land for installation, and heat consumption by region.

The evaluation of the impact in other sectors (mining, pulp & paper production, chemical industry, among others) is recommended. Moreover, a fair comparison between other technologies (PV, solar thermal) is encouraged to determine which technology can offer the highest environmental benefit.

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