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Green hydrogen and Solar EV City Concept in Santiago-Chile#

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ABSTRACT

Urban decarbonization is an important step in achieving carbon neutrality as urban population is expected to increase substantially for the next decades globally. This research evaluates the performance of a combined system of rooftop photovoltaics (PV) integrated with Electrical Vehicles (EV) as batteries (PV+EV) and Green Hydrogen (GH_2) as energy storage for the Santiago Metropolitan Region of Chile using a techno-economic analysis. Several scenarios were analyzed including different years (2019 and 2030) reflecting declining costs of technologies, different technology combinations, and net billing system. In the simulations, the surplus renewable electricity from PV+EV is used to produce GH_2 through Electrolysis Cells (PEMEC) and stored in tanks. When the city's demand cannot be met by the PV+EV system, GH_2 is used to generate electricity through Fuel Cells (PEMFC) for the demand. Results show that for the PV + EV + NB scenario with the estimated costs of technologies in 2030, it is possible to supply 96% of the total electricity demand of the city with 97% CO_2 emission reduction and 37% cost savings. The surplus electricity from the system is used to generate green hydrogen and met the demand of the city, when PV generation is low. Therefore, we conclude that the proposed rooftop PV+EV+GH_2 system is a viable and effective option to deeply decarbonize the urban power system with local PV generation.

Keywords: Green hydrogen, photovoltaics, renewable energies, techno-economic analysis, electric vehicles, urban decarbonization.

NOMENCLATURE

Abbreviations	
GH_2	Green Hydrogen
PV	Photovoltaic
EV	Electrical Vehicles
PEMEC	Polymer Electrolyte Membrane Electrolysis Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
MR	Metropolitan Region of Chile
RE	Renewable Energy
NB	Net Billing System

1. INTRODUCTION

Renewable energy (RE) sources and Green Hydrogen (GH_2) have important roles in reducing the greenhouse gases generated by human beings, and at the same time, maintaining the living standards of today's society [1]. Solar photovoltaics (PV) is one kind of RE currently taking an important role in the energy transition process in energy supply. Nevertheless, its dependence on weather conditions and fluctuating behavior during the day, which is often opposite to electricity demand in winter, are challenges that need to be overcome to scale up its participation in the energy matrix. Green Hydrogen (GH_2) is taking a strong position as an energy carrier of RE. Its versatility allows it to be utilized as fuel as well as electricity. With the decreasing price of electrolysers and RE [2], GH_2 will be a promising option to store energy and use it as electricity by electrolysis when demand is high.

We employed techno-economic analyses to evaluate the viability of rooftop PV systems integrated with Electric Vehicles (EV) with a V2H/V2B (Vehicle to home/building) or V2G (Vehicle to grid) and GH_2 as an energy storage system in a city scale ("SolarEV City Concept"). To understand the impacts of declining cost trends on RE production, two scenarios were analyzed (Years 2019 and 2030), with different combinations of technologies (PV only and PV+EV) and the option of the Net Billing system (NB). The various scenarios allowed us to comprehend how consumers would behave based on their available energy storage and grid-sharing options. The surplus electricity produced by PV was considered for generating GH_2, through electrolysis technology. The concept "P2H2P" (Power to Hydrogen to Power) was considered in this study for its viability, transforming RE into Hydrogen and then transforming it again into

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electricity, when the RE coming from PV does not meet the demand.

The analysis was conducted for the Metropolitan Region of Chile (MR), which contains the capital city, Santiago. The region has high renewable potentials (solar and wind) with a population of 8 million people and an area of 15,000 km^2.

2. MATERIAL AND METHODS

2.1 Settings for rooftop PV systems

The system considers the installation of PV on the rooftop area available in the city. The rooftop PV generates electricity for each building to cover the electricity demand, and in some scenarios, for the EV demand. The surplus electricity from the PV system is injected into the grid and used for GH_2 production. The electricity load of the city, which includes the electricity consumption of EVs as well, is supplied with a specific order as following. First, the electricity load is met by the renewable electricity source of PV. Then, we assumed two scenarios, the "RE Deficit scenario" and the "RE Surplus scenario". In the "RE deficit scenario", after the PV direct supply, the load is met by the electricity produced from GH_2 coming from the tank and converted into electricity through fuel cells. If the demand is not fully supplied, electricity from EV batteries are used to cover the deficit. If the demand is still not totally covered, it is loaded from the grid, a nonrenewable energy source. In the "RE surplus scenario", the charging priority is given to the supply from EV batteries. If there is a remaining surplus, it will be used to produce GH_2 that is stored in the tanks.

2.2 Techno-economic analysis SolarEV City Concept

The System Advisor Model (SAM) [3] of NREL was used for the techno-economic analysis of the system Solar PV and EV, as RE source and battery. The present study takes as a reference the methodology already used by Kobashi, T. (2023) [4] in his study. This method considers the cash flow of the electricity supply, comparing the current system (grid-based) and the new system (PV-based). The viability of the system is evaluated by the Net Present Value (NPV) of the city.

The scenarios considered in the study were "2019 PV Only with Net Billing", "2019 PV Only without Net Billing", "2030 PV Only with Net Billing", "2030 PV Only without Net Billing", "2030 PV+EV with Net Billing" and "2030 PV+EV without Net Billing". For each scenario, the input information differs mainly in the system cost, the electricity load, and the available rooftop area for PV, owing to social development in different years. The information used for each scenario is listed in Table 1. Finally, the weather file was obtained from NASA, specifically from the Global Modeling and Assimilation Office [5].

Table 1. SAM Model Inputs

Parameter	Year 2019	Year 2030	Ref.
Population	7,915,199	8,688,263	[6]
Vehicles per capita	0.2	0.23	[7][8]
Annual Electricity load	23,335 [GW]	28,575 [GW]	[9][10]
Roof top area (70% of total area)	255 [km^2]	366 [km^2]	[11]
Total Battery Capacity	-	68.2 [GWh]	[10]
Battery Max. Power	-	10.2 [GW]	[10]
Project period	25 [yr]	25 [yr]	-

2.3 Electricity tariffs and net billing policy

The electricity tariffs in the Chilean power system differ depending on the type of consumers. For residential consumers, the tariff "Low Tension 1" (BT1) is applied with a connected power lower than 10 [kW]. The weighted average price of the BT1 tariff corresponded to 0.16 [USD/kWh] in 2019 according to the Chilean National Energy Commission [12]. In 2019, the Chilean government promulgated the Law No. 21,185 that established mechanisms to stabilize the increase of electricity tariffs [13]. The law dictates that the tariffs will be only modified by inflation rates. Therefore, for the year 2030 scenario, it is expected that the electricity tariff will be approximately 0.28 [USD/kWh], considering an inflation rate of 2.6%.

In Chile, since the year 2016, a net billing (NB) system has been implemented by Law No. 20,517. It indicates that a residential user that has a renewable electricity source under 100 [kW], can sell their surplus renewable electricity to the grid at a regulated price [[14]. The selling price for 2019 was 0.09 [USD/kWh] and for 2030 was 0.15 [USD/kWh].

2.4 System costs for "SolarEV City"

The costs of PV and EV in different years are shown in Table 2. The decreasing trend in RE technologies was considered in the study for the 2030 scenario.

Table 2. System Costs

Category	Value		Ref.
	Year 2019	Year 2030	
CAPEX [USD/W]	1.923	1.55	[15][16]
OPEX and Maintenance Expenditure [USD/kW-year]	20	15.81	[17]
EV battery Replacement cost [USD/kWh]	-	155	[18]

2.5 Hydrogen production and costs

Surplus electricity is injected into grid and used to feed GH$_2$ plant that incorporates a Polymer Electrolyte Membrane Electrolysis Cell (PEMEC). The produced GH$_2$ is stored in tanks. The present study assumes no constrains on the water supply in the analysis. The surplus electricity of the system is obtained from the SAM output, corresponding to the category “electricity from the system to the grid”. When the city needs additional energy, the GH$_2$ generates electricity through Polymer Electrolyte Membrane Fuel Cells (PEMFC) from the tank and injected into the grid.

2.8.1 Green hydrogen production cost

PEMEC technology is in the near term of commercial applicability, and prices are decreasing due to scale production [[19]. In this study, we consider GH$_2$ scenarios only for the 2030 scenario. Therefore, the system costs and efficiency of the PEMEC follow the current trends of this technology (Table 3).

Table 3. PEMEC system cost

Parameter	Unit	Value	Ref.
Capital cost 2030	USD/kW	720 -810	[19]
Replacement cost	Percentage of CAPEX/year	15%	[20]
O&M	Percentage of CAPEX	5%	[20]
Efficiency	kWh/kg H$_2$	52	[19][20]
Storage	USD/kg H$_2$	960.7	[21][22]

2.8.2 Electricity from green hydrogen costs

PEMFC technology was chosen for this study due to its flexibility, low operation temperature, and most importantly, quick start-up time and load [[23]]. PEMFC costs are shown in Table 4.

Table 4. PEMFC system costs

Parameter	Unit	PEMFC	Ref.
CAPEX	USD/kW	4,000	[24]
Replacement cost	USD/kW	3,000	
OPEX	USD/hr	0.01	

2.6 Green hydrogen time series analysis

Time series analysis was conducted to understand the GH$_2$ production and re-electrification dynamics during the first year of the system. The analysis was conducted using MATLAB software.

3. RESULTS

3.1 Techno-economic analysis

The results of the techno-economic analysis (Table 5) show that the PV+EV with NB scenario in 2030 has the highest NPV in the 25 years of the system life. In both scenarios, the “PV+EV with NB in 2030” and “PV Only with NB in 2030”, the maximum PV capacity is achieved, corresponding to 70% PV coverage of the total rooftop area of MR. However, since the PV Only scenario does not have a battery system such as EV battery, the generated electricity cannot be consumed within the city, resulting in higher grid electricity consumption (i.e., higher CO$_2$ emission).

Table. 5 Techno-economic analysis indexes

Scenario/parameters	2030 PV+EV		2030 PV Only		2019 PV Only	
	No NB	With NB	No NB	With NB	No NB	With NB
Energy [GWh/yr]	28,345	78,587	11,626	86,847	7,170	8,671
Net Present Value [mill.USD]	44,400	73,712	18,338	70,659	2,924	2,429
Electricity bill without system [mill.USD/yr]	9,517	9,517	7,959	7,959	3,714	3,714
Electricity bill with system [mill.USD/yr]	1,622	-6,578	5,240	-6,754	2,607	2,490
Simple payback period [yr]	4.0	5.1	4.0	5.6	7.7	8.3
Discounted payback period [yr]	4.6	6.9	4.7	7.3	11.6	13.4
Self-consumption	100%	44%	84%	15%	97%	88%
Self-sufficiency	79%	96%	34%	46%	30%	33%
Energy sufficiency	79%	218%	41%	306%	31%	37%
Cost Savings	27%	37%	6%	25%	2%	2%
CO$_2$ Emission Reduction	85%	97%	21%	28%	19%	21%

To better understand the performance of the system, following indexes were analyzed: self-consumption (how much electricity generated by PV is consumed within the city), self-sufficiency (how much electricity demand of the city can be supplied by locally generated PV electricity), energy sufficiency (annual electricity production from PV compared to the annual city demand of electricity), cost savings (how much energy cost can be saved by the installation of PV system) and CO_2 emission reduction [4].

The CO_2 emission reduction reached the highest value (98%) with the PV+EV With NP in 2030 scenario. The self-sufficiency in the same scenario represents 96%. However, the self-consumption is only 44%, which indicates that the energy produced by PV can supply 96% of the city's demand, but most of the energy is exported to outside of the city. For the "PV+EV" and "PV Only" With NB in 2030 scenario, the energy sufficiency has high values (218% and 306%, respectively). Showing that the electricity produced by PV is 2 or 3 times higher than the consumption of the city.

3.2 Hydrogen production

The production of hydrogen follows the trend of power surplus from PV (Fig. 1). There is a noticeable large excess of energy coming from PV during spring and summer (November to February) which is associated with increased hydrogen production (Fig. 1).

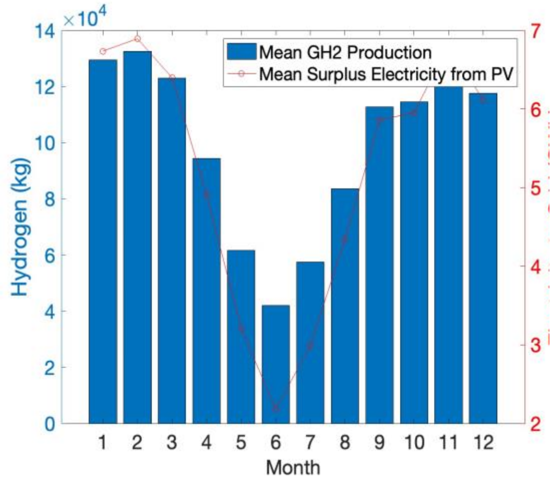

Fig. 1 Surplus electricity and GH_2 production

In the PV + EV with NB scenario in 2030, the surplus energy reached 45,455 [GWh/year]. This energy is injected into the grid since it is not being used either by households or EVs. Using the efficiency parameter of PEMEC it is possible to determine the quantity of Green Hydrogen that can be produced from the surplus electricity. The system can produce 874,138 [ton/year] of GH_2 with a daily maximum of 3,890 [ton/day].

The levelized cost of electricity (LCOE) from the PV system is used for the Net Billing price for the year 2030, which corresponds to 0.15 [USD/kWh]. As a result, the hydrogen production cost for this scenario is 8.34 [USD/kg].

The total electricity that the PEMFC can produce from GH_2 is 12,849 [GWh/year]. The expected production cost of the electricity from GH_2 is calculated with the system cost and the total generated electricity in one year. The results show that the electricity produced by the PEMFC has a cost of 0.82 [USD/kWh]. This price is slightly higher than the electricity tariff from the grid, established to be 0.28 [USD/kWh] by 2030.

The electricity that can be produced from GH_2 (12,849 [GWh/yr]) is around three times the electricity that needs to be imported from the grid (858 [GWh/yr]). These results show that the electricity demand of MR of Chile can be fully covered by rooftop PV as a source, and EV and GH_2 as storage.

3.3 Analysis of green hydrogen (GH_2) production

The 25-year lifespan of the hydrogen system was analyzed for the 2030 PV+EV with NB scenario. In the simulation, the system starts operation on January 1st, 2030, and the production of GH_2 starts on the first day of January 2030 due to the surplus energy production by PV in summer in the southern hemisphere. If GH_2 is not necessary for electricity production, it is kept in tanks. In the first month, PV and EV can cover all the demands of the city. Thus, all the produced GH_2 is stored in the tank.

The first electricity generation from GH_2 occurs on April 24th between 5:00 and 6:00 AM, which is approximately 0.58 GW. By that time, the accumulation of GH_2 in tanks is approximately 333,004 tons of hydrogen which can produce approximately 4,894 GW of electricity. The electricity demands increase between April and September for winter space heating demands. The peak occurs in June. On the other hand, the production of GH_2 from surplus electricity is lower during these months. Nonetheless, the GH_2 produced from

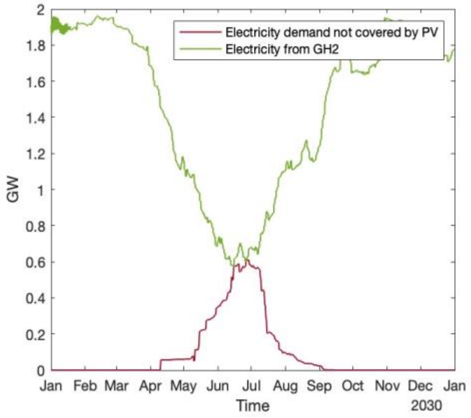

Fig. 2 Electricity demand not supplied by PV+EV (red) and potential GH_2 electricity production (green).

January to April (summer) is stored and it is available for the electricity demands of the city in winter. Figure 2 shows the monthly means of the electricity imports from the PV+EV system and the potential electricity that can be produced from the hydrogen tank.

The potential electricity that can be produced by GH_2 in tank, can fully supply the electricity to the city's demands in winter from the hydrogen stored in summer. This substantially reduces the consumption of grid electricity thus CO_2 emission from the fossil fuel power plants. During the 25 years of lifetime, the GH_2 plant produces around 19 millions of tons of hydrogen. This amount of GH_2 represents 2,293 [TWh] of electricity. After meeting the supply of the city, the remaining surplus hydrogen is around 17.5 million tons that can be used as fuel or exported outside of the city for the sectors difficult to abate CO_2 emissions (e.g., airplanes, ships, and industries).

Therefore, we conclude that by the rooftop PV systems integrated with the EVs, the PEMEC, and the PEMFC, the Santiago RM electricity demand can be fully supplied during the 25-year lifetime of the system (Fig. 3). The electricity load of the city can be mostly suppled from the PV + EV systems. The remaining demand can be met by the electricity generated through the GH_2 system.

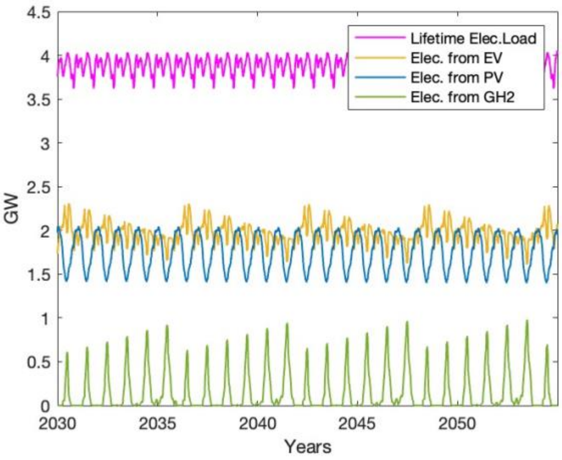

Fig. 3 Lifetime electricity loads supplied from PV, EV

4. DISCUSSION

The PV + EV + GH_2 system is shown to be effective and fully self-sufficient in supplying the Santiago MR electricity demands. The economic feasibility of two scenarios, "PV+EV" and "PV only" in 2030 show the promising results, where solar energy can play as an important energy source to supply the entire region's demands with a payback period of 7 years. Due to the NB policy, each household has an incentive to inject the surplus RE generated by the rooftop PV into the grid, and therefore, increase the economic performance of the PV system and expand optimal PV capacities. This policy also allows building owners to have larger savings that incentivize more citizens to install the PV systems.

Nevertheless, the price of the electricity generated from GH_2 0.82 [USD/kWh] is not competitive, compared to the electricity tariff (0.28 [USD/kWh]) from the grid by the year 2030. This indicates that building owners would opt to consume electricity from the grid (coming from non-renewable sources) due to its lower price. The price of the PV system in the simulation uses the cost of residential-scale projects. Thus, the cost of the PV system is higher than the cost of large-scale rooftop PV projects. Due to this, the electricity price coming from GH_2, which uses the PV surplus electricity, becomes higher.

Cost projections show that before the year 2050, electrolysers and renewable energy costs will further decrease significantly, and GH_2 will reach a production cost of 1 [USD/kg] for large-scale projects [25]. Considering the PV cost projection on a residential scale, the PV+EV with NB system can produce a GH_2 with a price of 4.22 [USD/kg] and electricity from GH_2 with a price of 0.26 [USD/kWh]. Therefore, to be competitive in the electricity market, a significant decrease in the costs of rooftop PV, EV, and GH_2 generation and/or policy support are necessary.

5. CONCLUSIONS

The proposed "PV+EV+GH_2" system can be considered as a feasible economic option to decarbonize the power system of Santiago MR. By the integrated systems of PV, EV, and GH_2, the entire city's electricity demand can be met without the need to consume power from non-renewable sources. Nevertheless, electricity production based on GH_2 is not competitive in the electricity market of the year 2030 owing to the still higher prices of the technologies. A significant decrease in residential PV cost is needed to make this system viable. The novelty of this system can be extended to other regions since GH_2 can be stored in the tanks and transported. GH_2 provides a clean energy option to off-grid areas or regions with low renewable energy potentials. Challenges are to build infrastructures allowing GH_2 to be transported for domestic, international, and industrial needs as a CO_2 emission free energy source.

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