

Modeling Residential Adoption of Solar PV in Qatar

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Abstract. We present an agent-based model for residential adoption of photovoltaic (PV) systems in Qatar where agents are defined as households within the Al Rayyan municipality in Doha. Each household corresponds to a villa-type accommodation, which is either owned or rented. The objective of the model is to evaluate PV adoption behaviors across these two household cohorts under diverse regulatory and incentive scenarios. The study suggests that the national goal of 20% electricity production through solar energy by 2030 can be facilitated by using current electricity subsidies to incentivize PV adoption, introducing a carbon tax, and extending the electricity tariff to all dwellers, citizens and expatriates alike.

Keywords: PV adoption; energy cost; energy policy; agent based modeling.

1 Introduction

This study analyzes the impact of home ownership, electricity subsidies, the introduction of a carbon tax, and the diffusion of innovation on the residential adoption of solar photovoltaic technologies (PV) in Qatar. The integration of any significant amounts of renewable energy into the power grid generates interconnected changes with deep and long-lasting effects on the technical, economic and social fabric of a nation. Designing the right policies to promote and regulate renewable energy is crucial in ensuring that the ensuing changes will have positive outcomes. In this paper, we take the first step towards developing a social simulation approach capable of supporting policymakers and other stakeholders to examine alternative energy policy scenarios in order to establish the optimal combination of incentives and regulations for the integration of solar renewable energy in Qatar's power grid.

Government institutions around the world have been developing financial incentive and regulatory frameworks to encourage utility companies and end-users to adopt solar and other renewable energy technologies. Financial incentives include measures such as the solar Investment Tax Credit in the US, and the Feed-in Tariff currently enforced in about 80 countries around the world [1]. Net Metering, Renewable Portfolio Standard, Tendering/Auctioning, and Renewable Energy Certificates are the most widely used regulations to promote the adoption of renewable energy technologies.

The right combination of incentives and regulations needs to be evaluated with reference to the governance, legal, economic and cultural context of each geopolitical entity to maximize the adoption of solar and other renewable energy technologies.

For example, the Feed-in Tariff in combination with Net Metering has greatly benefited the adoption of renewable energy in several European countries, but its adoption has been relatively slow in North America, where other forms of incentivization such as the solar Investment Tax Credit have played a stronger role.

Qatar and other GCC countries have economic and energy policy regimes that are rather different from those found in countries with significant renewable energy penetration. Policies developed elsewhere may not be applicable or successful. For example, tax credit incentives cannot be adopted in Qatar due to the absence of income tax. Moreover, electricity is highly subsidized in all GCC countries and free for private citizens in Qatar. According to the International Energy Agency (IEA), electricity subsidies in Qatar averaged \$2.1bn in the period 2012-14 (Table 1). Natural gas has also been strongly subsidized, as shown in Table 1, and a significant part of natural gas subsidies supports electricity costs since electricity is almost entirely produced from gas in Qatar.

Table 1. Electricity and natural gas subsidies in Qatar (billion USD). *Source:* IEA [2].

<i>Product</i>	<i>2012</i>	<i>2013</i>	<i>2014</i>
Electricity	2.1	2.0	2.3
Gas	1.6	1.5	1.6

Home ownership status is also a determinant factor in modeling PV adoption in Qatar since citizens do not pay for utilities and only citizens can buy properties in most municipalities. Others living in these municipalities as renters tend to be expatriates or long-term residents. Because each household type has different electricity costs, incentives and regulations are likely to engender diverse PV adoption behaviors. In developing a PV adoption model for Qatar, our objective is to evaluate the adoption behaviors of owner and renter households and explore how these may change in alternative energy policy scenarios.

2 Background

Complex-systems approaches, including agent-based and system-dynamics modeling techniques, have been used successfully in the development of decision support tools for policy evaluation of renewable energy generation systems in their geopolitical context. For example, Zhao et al. [3] propose a two-level simulation modeling framework to analyze the effectiveness of incentive and regulation policies on the growth rate of distributed PV systems. Paidipati et al. [4] describe a model of market penetration of rooftop PV in each of the 50 US states which takes into account the technical potential of rooftop PV and payback period for rooftop PV investments. The SolarDS model [5] simulates PV adoption on residential and commercial rooftops in the continental US through 2030 by aggregating regional PV adoption to the state and national levels, where lower PV costs were fostered including net-metering incentives and policies pricing carbon emissions of competing energy sources. Graziano & Gillingham [6] examined the spatial pattern of rooftop PV adoption in Connecticut tak-

ing into account housing density, share of renters vs. home owners, and the “neighbor effect” according to which adoptions increase in the vicinity of existing installations.

These and other simulation approaches to modeling the adoption of renewable energy represent important steps forward in understanding the impact of policy on solar PV adoption. However, these efforts are typically based on systemic assumptions about incentives and regulations for renewable energy such as tax credits, the Feed-in Tariff and Net Metering. These incentives and regulations do not apply to Qatar since there is no income tax, citizens have free electricity, the electricity tariff is strongly subsidized, and the Feed-in Tariff and Net Metering have not been implemented.

3 Approach

Following [7, 8], we develop an agent-based modeling approach where PV adoption is driven by cost. Agents represent two types of households: owners and renters. The lower the cost of electricity from PV, the more likely are household agents to adopt rooftop solar PV. Several factors can contribute to lower the cost of electricity from PV in the Qatari context including:

- the use of electricity subsidies and the portion of gas subsidies used for electricity production to incentivize PV adoption
- the introduction of a carbon tax
- the extension of electricity costs to Qatari citizens
- a neighborhood effect, which implements the diffusion of PV innovation as a percent discount on PV costs.

In the scenarios analyzed in this study, we assume the following settings for these factors (see section 4 for details):

- Redirection of 40% of electricity subsidies to renewable energy, which would lower the cost of PV by \$0.0232/ kilowatt hour (kWh)
- Redirection of 40% of gas subsidies used for electricity production to renewable energy, which would lower the cost of PV by \$0.0032/kWh
- Introduction of a carbon tax, which would lower the cost of PV by \$0.0048/kWh
- Extension of electricity costs to Qatari citizens, which would increase the electricity tariff for citizens from \$0 to \$0.02/kWh, in the timeframe addressed in this study
- A neighborhood effect, which implements the diffusion of PV innovation as a percent discount on PV costs in the following manner:
 - 15% discount on PV cost for a household that has not adopted yet and is adjacent to a household that has already adopted and has the same home ownership status (owned or rented)
 - 7.5% discount on PV cost for a household that has not adopted yet and is adjacent to a household with different home ownership status that has already adopted.

At the start of a simulation, the neighborhood effect is activated, and the base price of electricity from rooftop solar PV (PV cost) of \$0.1168/kWh (see section 4) is reduced as detailed in each of the following three scenarios:

1. *Business as usual: no measures are introduced to incentivize PV, and the neighborhood effect is active* – Reductions on PV cost for new adopters:
 - Expatriates (renters) and citizens (owners): neighborhood effect (15% or 7.5% of the cost of PV)
 - Expatriates: cost of electricity (\$0.02/kWh).
2. *40% of gas and electricity subsidies which currently support non-renewable energy are used to incentivize PV, the carbon tax and the neighborhood effect are active, and citizens continue to have free electricity* – Reductions on PV cost for new adopters:
 - Expatriates and citizens: neighborhood effect, cost of carbon (\$0.0048/kWh), electricity and gas subsidies (\$0.0264/kWh)
 - Expatriates: cost of electricity.
3. *40% of gas and electricity subsidies which currently support non-renewable energy are used to incentivize PV, the carbon tax and the neighborhood effect are active, and both citizens and expatriates pay for electricity* – Reductions on PV cost for new adopters:
 - Expatriates and citizens: neighborhood effect, cost of carbon, electricity and gas subsidies, cost of electricity.

To verify the relative impact of the neighborhood effect and the carbon tax, scenarios are also simulated with the neighborhood effect and carbon tax active and deactivated.

Households adopt solar PV with a probability established by the logistic function in (1), where L is a scaling constant, e is the natural logarithm, x is the final cost of PV, and k is a parameter which determines the slope of the adoption curve. The final cost of PV is obtained by subtracting the following costs from the non-discounted cost of PV: (a) the electricity tariff; (b) the neighborhood effect, and (c) the carbon tax and subsidies when these are active. Since all our quantities are probabilities, we set $L = 1$. For the k parameter, we select a value that in the business-as-usual scenario yields a maximum PV market share of about 2.5% over 14 years ($k = 0.67$). This choice is motivated by the assumption that, in the absence of PV incentives and regulations, only innovators are likely to adopt. Innovators correspond to 2.5% of the entire market population according to Roger's adoption/innovation curve [9].

$$f(x) = \frac{L}{1+e^{-k*x}} \quad (1)$$

At each simulation tick, each household agent that has not adopted yet, is presented with the opportunity of doing so. Adoption is determined randomly according to the output of the logistic function in (1): a random probability p_r is generated, and if $(1 - f(x)) \geq p_r$, adoption occurs. This process is detailed in the pseudo-code below, where the cost of PV (nonDiscountedPVcost) and the utility tariff (UtilityTariff), the carbon tax (CO₂tax), and the k parameter are as set at the start of the simulation.

We simulated the three scenarios described above and their variants, using the Re-past environment [10]. Each simulation was cycled for 14 years, with each simulation

tick corresponding to a year, so as to have PV adoption results relative to the 2030 Qatar target of 20% solar energy penetration [1].

```

if hasSolar(Household) = false
  Pa = probabilityToAdopt
  Pr = Random-float 1 % generate random number < 1
  if Pa ≥ Pr
    then hasSolar(Household) = true
    else hasSolar(Household) = false.
probabilityToAdopt = 1 - (1 / (1 + e-(k * finalPVcost))).
  finalPVcost = nonDiscountedPVcost - UtilityTariff -
  neighborhoodEffect - CO2tax - subsidies.
neighborhoodEffect =
  if hasNeighborWithSolar(Household,Neighbor) = true
    if sameOwnershipType(Household,Neighbor) = true
      PVcost * 0.15
    elseif sameOwnershipType(Household,Neighbor) = false
      PVcost * 0.075
    elseif hasNeighborWithSolar(Household,Neighbor) = false
      0.

```

Comparing simulation results (200 iterations * 14 ticks) for the entire population (19,594 households) and for a 4.6% sample (900 households) in the business-as-usual scenario with $k = 0.67$, we found that the average rate of PV adoption only showed a 0.19% difference: 1.03% for the entire population vs. 1.22% for the 4.6% sample. Also, we noticed that the average number of total and new adoptions by year present the same pattern every 200 iterations and multiple aggregations of 200 iterations (e.g. 1000 iterations), as shown in Fig. 1. We therefore concluded that we could simulate scenarios using a 4.6% population sample (900 households) and 200 iterations with no loss of generality, while reducing simulation time from days to minutes.

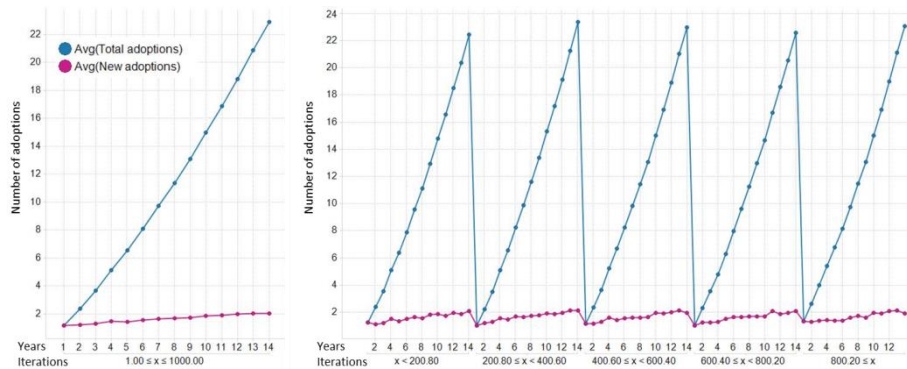


Fig. 1. Average number of total and new PV adoptions by year, over 1000 iterations (left graph) and 5 consecutive partitions of the same 1000 iterations (right graph).

4 Data

We used the household data from the most recent Qatar census [11], focusing on villa accommodations in the Al Rayyan municipality. These include 19,594 units housing 129,831 individuals, of which 21% were owned and 79% rented.

As base reference for PV costs, we used the recent award by the Dubai Electricity and Water Authority to Acwa Power for a 200MW solar plant, at a fixed rate of \$0.0584/kWh over 25 years [12]. This level of PV cost for utility scale solar plants is becoming a standard in the Middle East, as corroborated by an even lower recent power purchase agreement secured by the Saudi Electric Company that will provide solar energy at \$0.049/kWh for a 50 megawatt PV plant [13].

We calculated the PV costs of rooftop solar by doubling the price of utility-scale solar, following a recent study by the Brattle Group according to which the cost of energy from a 300MW utility-scale PV solar plant is roughly one-half the cost energy from an equivalent 300 MW of 5kW residential-scale systems [14]. The final cost of rooftop solar PV was thus set at \$0.1168/kWh.

We used data from 2013, since 2013 was the most recent year for which data about total primary energy supply from natural gas and natural gas used for electricity production in Qatar were available from IEA. Electricity costs and subsidies were calculated with reference to the following 2013 data from IEA, and Kahramaa (Qatar's utility transmission and distribution company):

- Average electricity tariff for residential villas: \$0.02/kWh
- Electricity subsidies: \$2,000,000,000 [2]
- Gas subsidies: \$1,500,000,000 [2]
- Electricity production/output: 34,668,000,000 kWh [15]
- Total primary energy supply from natural gas (production – exports): 39,233 Kilotonne of oil equivalent (KTOE) [16]
- Natural gas used for electricity production: 7,329 KTOE [16].

Electricity subsidies per kWh were set at \$0.058 by dividing electricity subsidies by electricity production/output. Additional subsidies were calculated as the portion of subsidies for natural gas used in electricity production. These subsidies were set at \$0.008/kWh by

1. Calculating the percentage of natural gas used for electricity production (19%) as the quotient of natural gas used for electricity production divided by total primary energy supply from natural gas
2. Taking the percentage of natural gas used for electricity production from the total gas subsidies and dividing it by the number of kWh of electricity produced.

The resulting cost of electricity before subsidies is \$0.086/kWh and consists of \$0.058/kWh of electricity subsidies, \$0.008/kWh of gas subsidies, and the average Kahramaa tariff of \$0.02/kWh for residential villas.

The carbon tax was set to \$8 per metric ton of carbon dioxide equivalent (tCO₂e) with reference to the spot market prices of EU Emission Allowances [17], according to which the price of carbon has varied from €5.47-€8.63 per tCO₂e in the last year. The relative carbon tax per kWh was established as \$0.0048 assuming that

- 10.11 cubic feet of natural gas are needed to generate 1 kWh [18]
- 10.11 cubic feet of natural gas are equivalent to 11,211.99 Btu [19]
- Natural gas produces 0.000117lb of CO₂ for each Btu generated [20].

We set the neighborhood effect as a maximum discount of 15% on PV costs following [8]. The dependence between discount rate and home ownership status is motivated by the fact that sharing the same home ownership status in the Al Rayyan municipality implies some level of socioeconomic homogeneity (i.e. citizen vs. expat or long-term resident). Socioeconomic homogeneity provides the basis for tighter social network structures and shared belief systems that have been recognized as promoting the extent of innovation diffusion [21, 22, 23].

5 Results

Table 2 provides the average percentage rates of total PV adoptions for each of the three scenarios by owners, renters, and both. Average percentages were computed across 200 iterations of each scenario simulation at the highest point of adoption (year 14). Results for the three scenarios are shown with the neighborhood effect (NE) active (base scenario) and deactivated. Results for scenarios 2 and 3 are also given with the carbon tax (CT) active (base scenario) and deactivated.

Table 2. Rates of PV adoptions at year 14 averaged over 200 iterations of each scenario for 900 households, of which 189 owned and 711 rented, in Doha’s municipality of Al Rayyan.

Scenarios	% of total PV adoptions	% of PV adoptions by owners	% of owners who adopted	% of PV adoptions by renters	% of renters who adopted
<i>1. Business as usual</i>					
• Base scenario	2.53%	0.17%	0.79%	2.37%	3.00%
• NE deactivated	1.75%	0.11%	0.52%	1.64%	2.08%
<i>2. 40% of subsidies and CT for PV; free electricity for citizens</i>					
• Base scenario	75.16%	1.29%	6.14%	73.87%	93.51%
• NE deactivated	49.78%	0.67%	3.17%	49.12%	62.18%
• CT deactivated	68.98%	1.28%	6.08%	68.70%	89.97%
<i>3. 40% of subsidies and CT for PV; citizens pay for electricity</i>					
• Base scenario	93.43%	19.43%	92.52%	74.00%	93.68%
• NE deactivated	62.43%	13.14%	62.57%	49.29%	62.39%
• CT deactivated	86.76%	18.15%	86.44%	68.84%	86.84%

The expected rate of PV adoption is very low in the business-as-usual scenario, while it increases dramatically when subsidies and the carbon tax are used to incentivize PV adoption (base scenarios 2 and 3). The extension of the electricity tariff to

citizens (base scenario 3) shows a strong impact raising the expected rate of adoption from 75.16% (base scenario 2) to 93.43% (base scenario 3). The neighborhood effect exhibits a strong impact across all scenarios. The use of the carbon tax (\$8/tCO₂e) to incentivize PV adoption has a modest impact, as shown by the 7% decrease in expected adoption rates when the carbon tax is deactivated in scenarios 2 and 3 respectively.

Figure 2 displays the expected market shares (total adoptions) and adoption curves (new adoptions) for the three base scenarios in Table 2 as percentage averages by year. With scenario 1, the market share and adoption curves display an overall trend of slow continuous growth. With scenarios 2 and 3, the market share and adoption curves display a pattern typical of innovation adoption (Rogers 1962): the adoption curve rises quickly in early years reflecting the behavior of the early adopter and early majority consumer cohorts, and then displays a downward trend in later years typical of late adopters and laggards. The market share curve does not reach full saturation in either scenario, but it displays a pattern that preannounces such an outcome in the near future, especially in scenario 3 where market share achieves a 93.43% level of saturation at year 14.

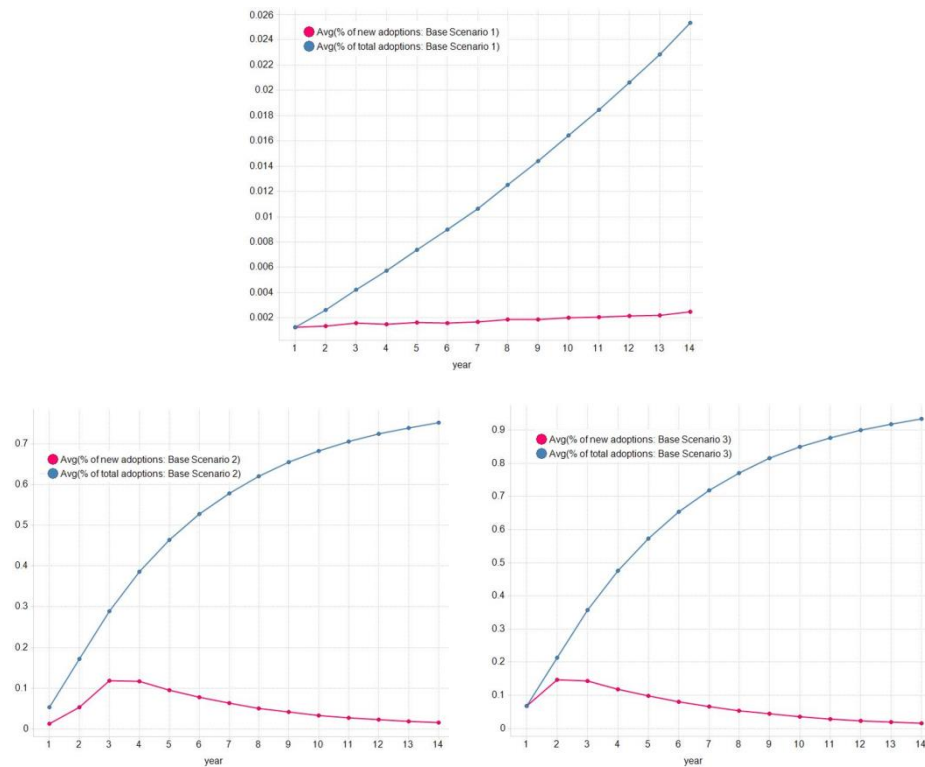


Fig. 2. Expected market shares (total adoptions) and adoption curves (new adoptions) for the three base scenarios in Table 2 as percentage averages by year.

6 Discussion

The results described in section 5 can be used to understand how much consumer demand for electricity in the Al Rayyan municipality can be met through solar energy in each of the three PV adoption scenarios. We can do so by

- Establishing the yearly electricity demand for the residential villa population in Al Rayyan
- Calculating the yearly yield for a reference PV system for each villa (e.g. a 5 kW PV system)
- Assessing how much of the yearly electricity demand can be met through the adopted PV in each scenario.

We can quantify electricity demand with reference to Kahramaa's estimate for yearly per capita consumption, net of transmission and distribution losses and bulk industrial consumption, of 11,100 kWh (KM 2015). The consumption for residential villa population in Al Rayyan can therefore be estimated at 1,441,124,100 kWh, by multiplying the yearly per capita consumption (11,100 kWh) by the residential villa population in Al Rayyan (129,831).

The expected yearly kWh yield of a reference PV system can be established as the product of the PV system capacity in kW, the yearly kWh per m² total of solar Global Horizontal Irradiation (GHI),¹ and a DC to AC derate factor for PV systems² – see [24] for details. For example, given the 2013 GHI of 2,169 kWh/m² for the area including Al Rayyan,³ and a DC to AC derate factor of 0.77, the yearly yield of a 5kW PV system would be about 8,351 kWh.⁴

Finally, we can estimate the amount of consumer electricity demand that can be met through 5kW PV systems in each of the three scenarios as follows:

- Determine the number of PV systems available in each scenario
 - (adoption rate * the number of villas) / 100
- Measuring the total yearly kWh generated by PV in each scenario
 - number of PV systems * yearly yield of a 5kW PV system
- Estimate the amount of consumer electricity demand met through 5kW PV systems in each scenario
 - total yearly kWh generated by PV / total electricity demand.

According to these estimations (Table 3), as much as 8.53% of consumer electricity demand from residential villas in Al Rayyan can be met in a scenario where PV is

¹ GHI is the relevant source of solar irradiation for non-concentrating PV systems [25].

² See <http://rredc.nrel.gov/solar/calculators/pvwatts/system.html> for details on the PV system derate factor.

³ Measurements provided by the high precision solar radiation monitoring station operated by the Qatar Environment and Energy Research Institute in Education City, Al Rayyan, Qatar (25.33°N, 51.43°E) – see [26] for details.

⁴ Since we currently do not have plane of array irradiance (POA) measurements for Al Rayyan, these calculations are made under the assumption that PV panels are installed horizontally. A higher yield may be obtained by determining the appropriate POA as a function of time for Al Rayyan (see <https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/plane-of-array-poa-irradiance/> for details on the POA calculation).

incentivized using the carbon tax (at \$8/tCO₂e) and 40% of gas and electricity subsidies which currently support non-renewable energy to incentivize (scenario 2). An additional 2.08% can be achieved by extending the electricity tariff to citizens (scenario 3). Only 0.29% of electricity consumer demand would be met by PV according to our model in the “business as usual” scenario (scenario).

Needless to say, these conclusions are only indicative of how PV adoption may play out in the context under consideration, since the model presented in this paper does not take into account many other important factors, such as: PV financing schemes; the PV-suitability of individual villas in terms of electricity productivity due to architectural features and position in the power grid; the introduction of Feed-in Tariff and Net Metering; de-regularization of the energy market, the introduction of dynamic electricity pricing, and a more precise calculation of yearly kWh yield of a reference PV system (see footnote 4). In future work, we plan to include these factors in our model of PV adoption to achieve higher reliability.

Table 3. Percentage of electricity consumer demand in Al Rayyan villas that can be achieved in each of the three scenarios in Table 2 (with reference to 2013 data).

<i>Scenarios</i>	<i>Electricity consumer demand met by PV</i>
Scenario 1	0.29%
Scenario 2	8.53%
Scenario 3	10.62%

7 Conclusions

Qatar plans to generate 20% of its electricity needs from solar energy by 2030 (REN21). To achieve this objective, PV adoption by households is necessary because of the difficulty in finding available land. Moreover, solar plant installation in remote areas would incur additional infrastructure costs for transmission lines. The study presented in this paper provides a first step toward validating scenarios of incentive and regulatory measures in a simulation environment that makes use of real-world knowledge about energy related costs. The initial results of our study suggest that the national goal of 20% electricity production through solar energy by 2030 can be facilitated by using current electricity subsidies to incentivize PV adoption, extending the electricity tariff to all dwellers, i.e. citizens and expatriates/long-term residents alike, and introducing a carbon tax.

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