Proactive Distributed Renewable Energy Resources (DRER) for Powering Tomorrow

Luis Gautier and Mahelet G. Fikru

Abstract The production and consumption of cleaner energy by distributed renewable energy resource (DRER) owners, sometimes referred to as prosumers, is expected to increase over the next few decades. With energy storage still remaining a costly investment, DRERs are actively looking for ways to match their peak onsite renewable generation with increased consumption to enhance their self-consumption rate. Despite a growing economics literature presenting energy production–consumption decisions by prosumers, there are not many studies characterizing DRER owners that proactively manage their energy accordingly. Building on past studies, we present a model of a DRER owner that maximizes utility to determine her rate of self-consumption after making energy production and consumption decisions. Our results suggest that a proactive DRER owner exhibits a relatively higher level of self-consumption if she cares enough about the carbon footprint coming from her energy consumption decisions. This points to the need for designing customized policy interventions based on how DRER owners view carbon emissions, ranging from no intervention with higher degrees of carbon disutility to using price incentives to encourage production and consumption of energy by the DRER owner.

JEL Classification Q4, Q2

Keywords Carbon emissions · Utility · Energy policy · Smart cities · Green electricity · Energy management

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1 Introduction

Distributed renewable energy resource (DRER) owners are decentralized energy producers that invest in renewable energy technologies such as rooftop solar photovoltaic (PV) and small-scale offshore wind turbines to primarily satisfy their demand for *locally produced cleaner* energy. DRERs are often referred to as *prosumers* to highlight their role in energy production and consumption (Fikru, 2019). In addition to the availability of a reliable two-way electric flow infrastructure and system, feed-in-tariffs and net-metering provisions incentivize DRER owners to export their excess electricity (if any) to the electric grid for some credit or compensation. The production and consumption of renewable energy by DRER owners is expected to increase over the next few decades, in part due to favorable policy incentives designed to achieve climate change goals, and in part due to consumer preferences for alternative energy-generating options featuring attributes such as reduced grid dependency, energy independence, and local generation (EEA, 2022). Related to this, energy storage or batteries are proposed as the most technically feasible approach to achieving objectives related to grid resiliency and energy independence.

Energy storage also plays an important role in strengthening the resilience of communities that rely on renewable energy by addressing the variability and intermittent nature of renewable energy generation, providing backup power, stabilizing the grid, and offering a sustainable and decentralized energy solution. However, the adoption of energy storage systems with renewable energy technologies (e.g., bundle solar purchase with batteries) faces significant cost barriers. For example, the initial capital investment for purchasing and installing energy storage technologies can be substantial, posing challenges for DRER owners, especially those with limited financial resources. As a result, prosumer communities need to adopt other proactive strategies in energy management through behavioral changes (Frederiks et al., 2015; Hafner et al., 2019). For instance, previous studies suggest that prosumers could actively match onsite generation with consumption patterns to reduce electricity bills or load shifting (Wittenberg & Matthies, 2016; Fikru, 2020), adopt energy-saving behavior, or invest in energy-efficiency improvements with solar installations to lower energy needs (Fikru, 2021).

A *proactive DRER owner* is an energy producer who not only consumes some of the energy she generates locally (self-consumption) but also actively participates in energy management, matching generation to direct consumption. She takes on a proactive role in managing her energy resources, including renewable energy generation and consumption. For instance, she may adjust her energy usage based on real-time data, optimizing energy consumption when renewable energy generation is high and reducing consumption during periods of low renewable energy availability. Despite the important role of proactive DRER owners in building resilient prosumer communities and facilitating energy transition and decarbonization goals, the economic literature offers little insight into the self-consumption decision of proactive DRER owners.

We address this gap by using the production–consumption model of the prosumer featuring the double optimization procedure (Fikru, 2020; Sanstad, 2011) to characterize the utility-maximizing rate of self-consumption of locally produced cleaner energy by the proactive-DRER owner. We define a proactive DRER agent as one that proactively manages self-consumption with utility maximization objectives, in addition to optimally choosing energy consumption and production levels (by maximizing utility and net revenue functions, respectively). The study addresses the following research questions: (1) What is the relationship between the rate of self-consumption on site and the percentage of energy demand offset by renewable generation? (2) To what extent should proactive DRER owners match their local generation with direct consumption (optimal self-consumption rate)? (3) How is the self-consumption rate, either exogenously given or optimally chosen (endogenous), affected by the degree to which a DRER owner cares about her carbon footprint?

The double optimization framework (i.e., maximizing two objective functions by the same agent or decision-maker) is a fast-growing approach to modeling energy-related decision-making (Fikru & Awuah-Offei, 2022). For instance, Fikru and Gautier (2023) argue that prosumers decide on energy consumption level by maximizing a utility function and decide on renewable energy generation by maximizing a net revenue function, where the relationship between energy consumption and generation is nonlinear. Due to feed-in tariffs or net-metering/billing requirements, prosumers typically earn credit or compensation by exporting their excess generation into the grid, which in turn incentivizes a lower self-consumption rate. Thus, depending on the extent of their energy management or self-consumption rate, which is assumed exogenous in previous studies such as Fikru and Gautier (2023), their optimal rate of onsite generation may increase (large marginal revenue gains) or decline (small marginal revenue gains) with the self-consumption rate. We add to this line of the literature by explicitly characterizing the utility-maximizing rate of self-consumption.

By explicitly characterizing the utility-maximizing rate of self-consumption as endogenous, this study draws implications for proactive prosumer behavior, such as load shifting and demand-response participation. A proactive prosumer goes beyond the basic role of producing and consuming energy by actively engaging in optimizing their energy practices. This includes adopting practices and strategies to enhance energy efficiency, adjusting consumption patterns to align with renewable energy availability, and potentially investing in energy storage solutions. The term *proactive* implies a conscious effort to optimize energy usage and contribute to a more sustainable and resilient energy ecosystem. Furthermore, this study explicitly factors in the role of disutility from carbon emissions (or environmental damage) from energy production, which is absent from existing works. The results have implications for understanding the additional benefits of the proactive-DRER owner model and designing policies to incentivize it accordingly.

Our results suggest that a proactive-DRER owner who maximizes utility to choose self-consumption rate exhibits relatively higher rates of self-consumption when she cares sufficiently about her carbon footprint. This result points to two potential types of DRER owners with different views on their carbon footprint, which gives rise to different optimal rates of self-consumption and onsite production. This implies that to achieve a smooth energy transition, policymakers could benefit from designing customized policy prescriptions depending on the extent of disutility or preference for reducing one's energy carbon footprints (Stanley, 2022). For instance, if a community cares enough about their energy carbon footprint, then active policy intervention may not be needed since DRER owners are proactive enough and also willing to consume a large portion of their own energy produced onsite. However, if a community does not care too much about its energy carbon footprint (e.g., only a small disutility from carbon emissions), then policy intervention may be needed to encourage the consumption of energy produced onsite by DRER owners.

To achieve energy independence, we explore the role of the financial compensation rate (e.g., dollar per kilowatt hour) at which the DRER owner exports excess energy. We show that this policy prompts the DRER owner to increase her consumption *and* production of her own energy, if she cares enough about her carbon footprint. A higher financial compensation rate prompts the DRER owner to increase the production of energy, which raises her demand for energy coming from the grid. But if the DRER owner cares enough about her carbon footprint, then she will be willing to substitute grid energy demand for the energy she produces onsite. Finally, as a case study, we discuss model implications in the specific context of member nations of the Gulf Cooperation Council (GCC). The GCC States, namely Bahrain, Kuwait, Oman, Qatar, Kingdom of Saudi Arabia (KSA), and the United Arab Emirates (UAE), are in a prime position to capitalize on distributed renewable generation. Their abundant solar resources, coupled with rising residential energy demand and progressive net-zero emissions policies, present an ideal opportunity for significant investment and growth in the DRER sector.

Section 2 presents the prosumer model along with energy consumption and production decisions when the onsite self-consumption rate is treated as exogenous. Section 3 discusses results when self-consumption rate is endogenous and determined by maximizing utility. Section 3 also presents additional analysis to highlight the role of the solar compensation rate and draw lessons for GCC States. Section 4 concludes with some policy implications.

2 The Prosumer Model

Consider a representative DRER owner or prosumer who owns the technology to generate renewable energy (e.g., using solar panels). The energy generation per period, q megawatt hours (MWh), represents a fraction $\phi \in (0, 1)$ of total energy demand or load, D, where $q = D\phi$ per period as in Fikru (2020) and Fikru and Gautier (2023). $\gamma \in (0, 1)$ denotes the percent of renewable energy generation that is used for onsite or self-consumption, and $1 - \gamma$ the excess (cleaner) energy exported back to the electric grid. Hence, energy exported to the grid is given by $\phi D(1 - \gamma)$ in MWh. We assume the government determines the compensation rate for excess clean energy (dollars per MWh), P_b, through which the prosumer is compensated for her excess generation.

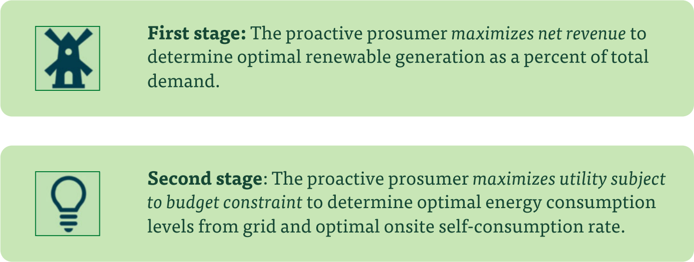
The DRER owner fulfills her net demand by buying energy from the local utility where the electric utility is assumed to offer both fossil-fuel-based energy, D_f, and greener energy, D_c (e.g., sourced from large-scale renewable energy projects). Thus, the total MWh of energy demand for the DRER owner is $D = D_c + \gamma\phi D + D_f$; that is, energy bought from the electric utility (fossil-based and greener) and self-consumption of DRER generation, $\gamma\phi D$.

The DRER owner perceives D_c and D_f as imperfect substitutes in consumption, where the parameter d denotes the degree of product differentiation and the degree to which the two products substitute each other in the function of providing electric services such as heating/cooling building spaces. If $d = 0$, then green and fossil-based energy are viewed as completely differentiated, and as d increases, the degree of substitutability between green and fossil-based energy increases.

According to the double optimization procedure presented in Sanstad (2011), the decision-making problem consists in first deciding what percent of energy demand or load the DRER will offset by onsite (renewable) generation, ϕ (based on maximizing a net revenue or net return function); and second, deciding how much energy to buy from the grid (by maximizing utility subject to a budget constraint). We solve the model via backward induction. That is, for a prosumer or DRER owner, we first solve for optimal D_f and D_c by performing a constrained utility maximization problem (given ϕ) and then solving for optimal ϕ by maximizing a net revenue function. For a proactive DRER owner, we first solve for optimal D_f, D_c, and γ by performing a constrained utility maximization problem (given ϕ) and then solving for optimal ϕ by maximizing a net revenue function. Figure 1 presents an illustration of the first- and second-stage decisions made by the proactive prosumer.

2.1 Energy Consumption Decision

The DRER owner chooses energy consumption levels, D_f, D_c, by maximizing the following utility function subject to budget constraints:



First stage: The proactive prosumer *maximizes net revenue* to determine optimal renewable generation as a percent of total demand.

Second stage: The proactive prosumer *maximizes utility subject to budget constraint* to determine optimal energy consumption levels from grid and optimal onsite self-consumption rate.

Fig. 1 Decision-making stages for proactive-DRER owner (Source: Authors' own elaboration)

$$\max_{D_c, D_f} U(D_c, D_f) = a_c D_c + a_f D_f - [(\beta_f D_f^2 + \beta_c D_c^2)/2 + d D_c D_f] + q_o - \frac{sE^2}{2} \tag{1}$$

where q_o is a numeraire good with price normalized to one, $\beta_f > d$ and $\beta_c > d$. Disutility from carbon (or greenhouse gas) emissions is captured by the term, $sE^2/2$, where the parameter s denotes the extent of the disutility from carbon emissions. We define net carbon emissions as E that affects the prosumer's utility where $E = D_f - D_c - \phi D$. That is, carbon emissions are proportional to consumption of fossil-fuel-based energy less greener energy bought from the grid, minus cleaner energy produced onsite. The presence of $s > 0$ captures the case of a DRER owner who cares about her net energy carbon footprint.

The prices of fossil-fuel-based energy, P_f, greener energy, P_c, and the compensation rate for excess energy, P_b, are assumed to be exogenous and given. The DRER owner maximizes Eq. (1) subject to her budget constraint, $M = P_c D_c + P_f D_f - (1 - \gamma) P_b \phi D$, where M is wealth or income. Solving the problem yields solutions for energy consumption levels (that is, amount bought from the electric utility) as follows: $D_c(\gamma, \phi, P_b, s, P_f, P_c)$, $D_f(\gamma, \phi, P_b, s, P_f, P_c)$.

2.2 Energy Generation Decision

Using solutions from the constrained utility maximization problem, $D_c(.)$ and $D_f(.)$, the DRER owner chooses optimal ϕ (renewable generation as a percent of demand) by maximizing the following net revenue function:

$$\max_{\phi} P_b(1 - \gamma)\phi D - C(q) - F \tag{2}$$

$C(q)$ and F denote variable and fixed costs of renewable generation, respectively, and the first term represents the revenue the DRER owner receives from selling excess energy produced onsite. The solution to Eq. (2) yields $\phi^*(\gamma, P_b, s, P_f, P_c)$, where substituting $\phi^*(.)$ back into energy consumption levels derived from constrained utility maximization gives equilibrium values such as $D_c^*(\gamma, \phi^*, P_b, s, P_f, P_c)$, $D_f^*(\gamma, \phi^*, P_b, s, P_f, P_c)$.

As a benchmark case, Fig. 2 presents the relationship between ϕ^* and γ when $s = 0$ and when D or total energy is not changing with ϕ ($dD = 0$) to avoid any solar rebound effects (see Appendix for a derivation of solutions). The benchmark case is for an exogenous or given γ and hence not (yet) capturing proactive measures undertaken by the prosumer.

The figure traces out what the optimal ϕ^* (renewable energy generation as a percent of total load) would likely be for different levels of γ (e.g., the ϕ^* could represent optimal PV sizing decision of the prosumer). The $\hat{\gamma}$ represents the level of onsite self-consumption that is consistent with the maximum renewable generation

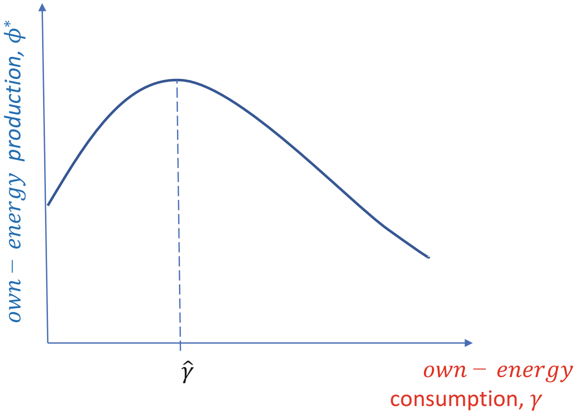


Fig. 2 Benchmark case: The impact of self-consumption rate on ϕ^* when γ is exogenous, $s = 0$, and $dD = 0$ (Source: Authors' own elaboration)

size as a percent of demand. As onsite self-consumption increases, the optimal renewable generation as a percent of demand initially increases (due to increasing net marginal benefits earned from compensation of excess generation), reaches a maximum, and then declines (due to lower volumes of generated energy available for compensation). The nonlinear relationship presented in the figure is consistent with prosumer models presented in previous studies (Fikru & Gautier, 2023). If $\gamma < (>) \hat{\gamma}$, the DRER owner consumes too little (much) of her own energy produced onsite. As a result, the marginal net revenue gains from producing onsite energy are large (small) enough, which prompts the DRER owner to produce more (less) energy onsite with increases in the self-consumption rate. In this benchmark case, γ is exogenous, and so the DRER owner is not necessarily proactive in matching generation with consumption to maximize utility.

3 A Proactive Approach for Prosumers

This section delves into the optimization of self-consumption rates by DRER owners, starting with a model where a proactive DRER owner determines the optimal rate of onsite self-consumption, considering both the utility derived from energy consumption and the disutility from pollution. The second subsection explores the role of the solar compensation rate, examining how changes in this rate influence the DRER owner's decisions about energy production and consumption. The section concludes with a discussion of lessons for GCC States illustrating how insights gained from the model presented in this study could inform policymaking.

3.1 Utility Maximization and Carbon Footprint

The proactive DRER owner maximizes utility to determine the optimal rate of onsite self-consumption, γ, in the presence of disutility from pollution, $s > 0$, simultaneously with demand for energy coming from the grid, D_c and D_f. That is, in addition to maximizing utility to determine energy consumption levels, the proactive prosumer also maximizes utility to choose optimal onsite consumption rate subject to budget constraints as before:

$$\max_{\gamma, D_c, D_f} U(D_c, D_f, \gamma) \tag{3}$$

From Eq. (3) we obtain D_c, D_f, γ as functions of ϕ and prices. To solve the model, we substitute these into Eq. (2) and obtain the equilibrium ϕ as a function of prices. To complete the characterization of the equilibrium, we substitute ϕ back into D_c, D_f, γ, which gives these as functions of prices and exogenous parameters of the model.

The utility-maximizing rate of onsite self-consumption is represented by γ^u. We compare the $\hat{\gamma}$ presented in Fig. 2 with the case where the proactive DRER owner chooses γ via utility maximization in the presence of disutility from pollution, $s > 0$. In particular, we characterize the γ that maximizes utility, $dU/d\gamma = 0$, and evaluate it at $d\phi^*/d\gamma$ in Fig. 2. If the sign is positive (negative), then $\hat{\gamma} > (<) \gamma^u$, where γ^u is optimal self-consumption rate. The Appendix formally derives this result.

We find that the DRER owner's utility-maximizing rate of self-consumption, γ^u, is greater than $\hat{\gamma}$, if the prosumer cares sufficiently about her carbon footprint coming from grid energy consumption, i.e., s is large enough, $s > \bar{s}$. In this case the higher percent of consumption of own energy reduces the demand for energy coming from the grid (i.e., D_c and D_f fall) and, as a result, the production of own energy falls. That is, we do *not* see the DRER owner increasing her production of own energy, rather she just increases her self-consumption rate. Because she cares enough about her carbon footprint (s is large enough), she is willing to consume more of her own renewable energy and at the same time give up the extra income coming from selling energy back to the grid.

Similarly, if the DRER owner cares little about her carbon footprint coming from energy consumption (i.e., s is small enough, $s < \bar{s}$), then her utility-maximizing self-consumption rate is less than $\hat{\gamma}$. This is because of two reasons. First, by consuming less of her own energy, she is able to sell a larger share of the energy she produces onsite and, therefore, generate extra income to afford additional energy from the grid. It is noteworthy that in this case the DRER owner is willing to consume less of her own energy because by doing so she can generate sufficient extra income by selling a larger share of energy back to the grid instead of increasing own energy production. Second, in this case, the DRER owner exhibits little disutility from emissions, and so she is willing to consume more energy from the grid even as this means a higher carbon footprint. Results are summarized in Fig. 3.

These results suggest that there are two types of proactive DRER owners for which two policy recommendations may be prescribed: one where no policy

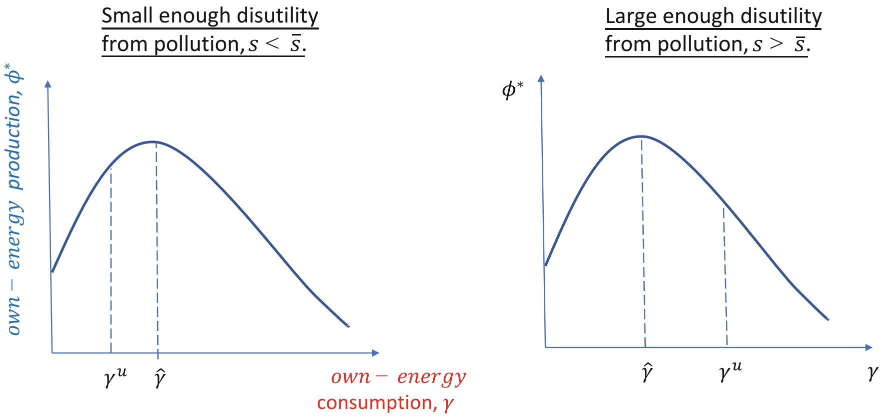


Fig. 3 Utility-maximizing self-consumption rate, γ^u, for relatively large or small disutility from carbon emissions (Source: Authors' own elaboration)

intervention is needed since DRER owner cares enough about her carbon footprint, and another where policy is needed to encourage consumption of onsite energy.

To further elaborate on the relevance of s, we argue that the DRER owner raises her utility-maximizing share of own energy consumption, γ^u, if she cares enough about her carbon footprint from grid energy consumption. In this case the DRER owner's gains from increasing own energy consumption to lower emissions more than offsets the reduction in income from selling energy back to the grid (DRER owner consumes more and therefore sells less of her own energy). There are two effects at play. First, if the DRER owner cares enough about her carbon footprint, then an increase in s lowers (raises) the consumption of default (clean) energy from the grid, where total grid energy consumption falls. This reduction in grid energy consumption leaves room for the DRER owner to increase the consumption of her own energy, γ^u.

Second, an increase in s prompts the DRER owner to increase her own energy production, ϕ, because doing so compensates for the reduction in grid energy consumption and enables the consumption of additional onsite renewable energy. In the Appendix we formally show that $d\gamma^u/ds > 0$, if the disutility from emissions, s, is large enough; we also show the case where the disutility from emissions is small enough and so $d\gamma^u/ds < 0$. The result differs from the analysis in Fig. 3. While Fig. 3 compares the exogenous and endogenous utility-maximizing share of own energy consumption ($\hat{\gamma}$ and γ^u), here we focus on the change in the endogenous utility-maximizing share of own energy consumption given a change in the disutility from emissions.

3.2 The Role of Compensation Rates in Prosumers Decisions

In this subsection, we comment on the extent to which DRER owners could enable grid independency by looking at the role of the compensation rate for excess clean energy, P_b, on ϕ^* and γ^u. The analysis indicates that an increase in the compensation rate induces the DRER owner to increase her own energy production, but this also prompts additional grid energy consumption (both default and clean energy). The additional grid energy consumption comes from the extra income the DRER owner generates by producing more onsite energy and selling any excess. In the absence of the rebound effect (i.e., total energy demand remains constant), the increase in default and clean grid energy consumption prompts the DRER owner to reduce the consumption of own energy (γ) since now she is consuming more energy from the grid. This result suggests that the compensation rate may not be entirely consistent with a policy approach aimed at reducing grid dependency. In the Appendix we formally show this result.

We combine the results from the preceding paragraphs to characterize changes in the share of total energy demand met by the energy consumed onsite, $\phi^*\gamma^u$, in terms of the elasticities of onsite energy production and consumption. Since ϕ^* and γ^u are functions of P_b and s, total differentiation gives (dropping the $*$ and u superscripts)

$$\frac{d(\phi\gamma)}{\phi\gamma} = \left[\epsilon_{\phi P_b} + \epsilon_{\gamma P_b}\right]\frac{dP_b}{P_b} + \left[\epsilon_{\phi_s} + \epsilon_{\gamma_s}\right]\frac{ds}{s} \tag{4}$$

where $\epsilon_{\phi_s} = (s/\phi)(\partial\phi/\partial s) > 0, \epsilon_{\phi P_b} = (P_b/\phi)(\partial\phi/\partial P_b) > 0, \epsilon_{\gamma_s} = (s/\gamma)(\partial\gamma/\partial s), \epsilon_{\gamma P_b} = (P_b/\gamma)(\partial\gamma/\partial P_b) < 0$. Intuitively, the share of total energy demand met by the energy consumed onsite depends on how sensitive the DRER owner is when it comes to producing (ϵ_{ϕ_s}, $\epsilon_{\phi P_b}$) and consuming (ϵ_{γ_s}, $\epsilon_{\gamma P_b}$) energy onsite. If the DRER owner is relatively more sensitive to changes in the production of energy onsite (that is, if changes in $\phi\gamma$ are driven primarily by changes in ϵ_{ϕ_s}, $\epsilon_{\phi P_b}$), then an increase in the compensation rate ($dP_b > 0, ds = 0$) raises the share of total energy demand met by the energy consumed onsite. Similarly, for a DRER owner who becomes more concerned about her carbon footprint ($dP_b = 0, ds > 0$), the share of total energy demand met by the energy consumed onsite also increases. But Eq. (4) also captures the trade-off between higher/lower levels of the compensation rate for a DRER owner who becomes more ($ds > 0$) or less ($ds < 0$) concerned about her carbon footprint; that is, setting Eq. (4) equal to zero gives

$$d(\phi\gamma) = 0 \Leftrightarrow dP_b/P_b = -\left[\frac{\epsilon_{\phi_s} + \epsilon_{\gamma_s}}{\epsilon_{\phi P_b} + \epsilon_{\gamma P_b}}\right] ds/s \tag{5}$$

where the term in brackets is positive as long as the DRER owner is relatively more sensitive to changes coming from the production of energy onsite. This result says that for a DRER owner who becomes more (less) concerned about her carbon footprint a proportional decrease (increase) in the compensation rate keeps the share of total energy demand met by the energy consumed onsite, $\phi\gamma$, unchanged. This illustrates the trade-off between a DRER owner's disutility from emissions and the compensation rate with implications on the design of effective compensation rate policy which we discuss below.

Now, if the DRER owner is relatively more sensitive to changes coming from the consumption of energy produced onsite (that is, if changes in $\phi\gamma$ are driven primarily by changes in ϵ_{γ_s}, $\epsilon_{\gamma P_b}$), then a myriad of cases arise: The denominator in Eq. (5) is negative and the sign of the numerator is ambiguous. This is because changes in γ depend on the level of the disutility from emissions, s. A large (small) enough s means $d\gamma^u/ds > (<)0$ and therefore $\epsilon_{\gamma_s} > (<)0$.

If the DRER owner does not care enough about her carbon footprint (in the sense that a small enough s means $\epsilon_{\gamma_s} < 0$), then the consumption of own energy falls even as the DRER owner becomes more concerned about her carbon footprint ($ds > 0$). In this case the term in brackets in Eq. (5) is positive (numerator is negative and denominator is negative), and so we still see the trade-off between the compensation rate and the DRER owner's disutility from emissions.

But if the DRER owner cares enough about her carbon footprint (in the sense that a large enough s means $\epsilon_{\gamma_s} > 0$), then the consumption of own energy rises as the DRER owner becomes more concerned about her carbon footprint ($ds > 0$). As a result, the term in brackets is negative indicating that the trade-off between the compensation rate and the DRER owner's disutility from emissions no longer holds. In this case, a DRER owner who cares enough about her carbon footprint and who also becomes more concerned about it raises her own energy consumption. This type of DRER owner can only offset her own energy consumption with a higher (not lower) compensation rate in order to keep constant the share of total energy demand met by the energy consumed onsite, $\phi\gamma$. This is because a higher compensation rate reduces the DRER owner's own energy consumption. More formally, the DRER owner who cares enough about her carbon footprint ($\epsilon_{\gamma_s} > 0$) and who becomes more concerned about it ($ds > 0$) increases her consumption of own energy (thereby raising $\phi\gamma$). But the same DRER owner decreases her consumption of own energy with a higher compensation rate (thereby reducing $\phi\gamma$) in order to keep $\phi\gamma$ unchanged.

Our analysis points to two policy-relevant results. First, policymakers may want to know how sensitive DRER owners are with respect to the production of energy onsite and the consumption of said energy. If DRER owners are sensitive to changes in the production of onsite energy, then a clear trade-off between the compensation rate and DRER owner's disutility from emissions arises. This result has implications for the design of the compensation rate: Those DRER owners who become less (more) concerned about their carbon footprint may need (not need) to see a higher compensation rate in order to raise the share of onsite energy consumed. But if DRER owners are relatively more sensitive to changes in the consumption of onsite energy, then this trade-off may not always hold thus pointing to a potentially different policy design when it comes to promoting energy consumption from onsite energy sources.

3.3 Lessons for GCC States

There is a growing number of studies analyzing the economic and environmental impacts of renewable energy generation in GCC States. For example, Alazemi (2017) finds that solar PV has a financial and environmental benefit in Kuwait; the study by Ramli et al. (2017) highlights the role of distributed generation in lowering dependence on fossil fuels for the Kingdom of Saudi Arabia; Salimi et al. (2022) examine solar energy development options for the United Arab Emirates (UAE) highlighting the need to move away from fossil fuels, and a related study by Sgouridis et al. (2016) examines the financial feasibility of renewable energy sources such as solar. Bhutto et al. (2014) argue for the potential role of renewable energy sources such as geothermal, solar, and wind power in facilitating sustainable energy in GCC States.

Table 1 presents energy statistics for GCC States based on data compiled from ESMAP (2020), IRENA (2019), and REN21 (2023). Solar potential is represented by the global horizontal irradiation which is measured in kilowatt hours (kWh) of solar energy per square meter per day. This metric measures the theoretical potential for the availability of solar resource at a given location and allows for comparing the natural conditions that allow for implementing any PV technology (ESMAP, 2020). Cumulative installed PV capacity is measured in megawatt peak (MWp) and describes the maximum output that a PV system can produce for the year 2018 (IRENA, 2019). Cumulative installed PV capacity per capita is measured in watt peak per population, and electric power consumption per capita (2014) is measured in kilowatt hours. The economic potential of PV is measured by using the levelized cost of energy-LCOE (US dollars per kilowatt hour, 2018) which measures the lifetime costs associated with construction and operation of the solar generation divided by electricity produced during this lifetime. The lower the LCOE the higher the economic potential. Each of the six countries have an average LCOE of \$0.08–\$0.09 per kilowatt hour, while the world average is at \$0.10 per kWh.

Table 1 shows that although GCC nations have higher solar potential, lower cost of PV and a higher per capita electric power consumption rate compared to world averages, the cumulative installed PV capacity (total and per capita) is significantly lower than world averages. Currently, the use of renewable energy in GCC States is minimal, where renewable production represents less than 1% of final energy consumption. However, a shift is potentially underway as GCC nations demonstrate commitment to combating climate change and supporting international efforts to build a more sustainable future by making progress toward reaching net-zero emissions. For example, Bahrain aims to increase its renewable energy usage to 10% by 2035, reducing its reliance on fossil fuels. The country is actively adopting regulations such as feed-in tariffs and premium payments and is considering governmental financial sources and tax incentives to support renewable generation targets. Saudi Arabia, a key player in the region, plans to source 50% of its energy from renewable sources by 2030 supported by several policy and regulatory frameworks such as feed-in tariffs, premium payments, and a mandate for

Table 1 Energy statistics for GCC States (Source: compiled from ESMAP, 2020; IRENA, 2019, and REN21, 2023)

Country	Solar potential	PV capacity	PV capacity/capita	Electric consumption/capita
Bahrain	5.8	5.0	3.2	19,597
KSA	6.2	89.3	2.6	9401
Kuwait	5.7	30.5	7.4	15,591
Oman	6.3	8.2	1.7	6446
Qatar	5.9	5.1	1.8	14,782
UAE	6.1	493.	51.2	11,088
World	4.9	2350.6	41.7	3829

renewable heat. The UAE is making progress, with the aim of increasing renewable energy use from 1% in 2020 to 31% by 2025, where government funding and tax breaks are expected to play a crucial role in the advancement of renewable energy projects. Similarly, Qatar has a renewable energy target supported by public finance mechanisms and fiscal incentives (REN21, 2023). Other nations such as Kuwait and Oman, although they do not have specific renewable targets, have some policies related to renewable energy use in power generation but lack a specific target.

Despite the low usage of renewable energy, GCC's ambitious goals reflect a growing recognition of the importance of transitioning to cleaner energy sources for long-term energy security and environmental sustainability (REN21, 2023). The high solar potential of GCC States (Table 1) suggests that DRERs can be a promising way toward achieving energy resilience. To encourage more investment in DRERs and decentralized generation, GCC states could consider several strategies. First, implementing policies that promote investment in DRERs, such as tax incentives, feed-in tariffs, or renewable portfolio standards, could provide a supportive environment for growth. Second, fostering public–private partnerships can help share the risks and benefits of investing in DRERs, making it a more attractive proposition for private entities including households. Third, increasing public awareness about the benefits of DRERs and decentralized generation through educational programs and public campaigns can drive demand and acceptance. Finally, upgrading the infrastructure of the grid to accommodate more decentralized generation, possibly through the use of smart grid technologies, can facilitate the integration of DRERs. While the transition to more decentralized generation will take time and strategic planning, these steps can help increase the use of DRERs in GCC states. Once DRERs are in place, GCC nations could encourage a proactive energy management approach as presented in this chapter.

The proactive DRER owner model presented in this chapter emphasizes the importance of self-consumption and proactive energy management, which could be beneficial for GCC nations striving for energy system resilience. For instance, the model suggests that DRER owners who care about their carbon footprint exhibit a higher level of self-consumption. This insight could guide GCC nations in designing customized policy interventions that encourage self-consumption and reduce carbon emissions. Policies could range from no intervention for those with higher degrees of carbon disutility to using price incentives to encourage energy production and consumption by the DRER owner.

Moreover, the model highlights the role of energy storage in achieving grid resiliency and energy independence. While the adoption of energy storage systems faces significant cost barriers, the model suggests that prosumer communities can adopt other proactive strategies in energy management through behavioral changes. These strategies include actively matching onsite generation with consumption patterns to reduce electricity bills or load shifting, adopting energy-saving behavior or investing in energy-efficiency improvements with solar installations to lower energy needs. By understanding and applying these strategies, GCC nations can enhance their energy system resilience, reduce their carbon footprint, and move toward a more sustainable and decentralized energy solution. This approach would not only align with the global trend toward cleaner energy production and consumption but also cater to the specific context and needs of GCC nations.

4 Concluding Remarks

We present an extension of the prosumer model in Fikru and Gautier (2023) by considering a proactive prosumer that actively matches onsite generation with real-time consumption via utility-maximizing goals. We refer to such prosumers as proactive DRER owners and show that depending on the degree to which such decision-makers care about energy carbon footprint, they would have a relatively higher or lower rate of self-consumption rate. While previous prosumer models (Fikru & Gautier, 2023) present the impact of exogenous self-consumption rates on optimal DRER sizes, we characterize the optimal self-consumption rate which is consistent with utility maximization goals. This new element allows us to characterize two different types of proactive DRER owners, namely, one who cares about the impact she has on the environment from consuming energy from the grid and that who does not care much. Hence, we propose two different types of policy recommendations based on these two types of proactive DRER owners. Overall, when it comes to energy consumption, we argue that a less aggressive policy approach should take place if the DRER owner cares sufficiently about her carbon footprint coming from consuming energy from the grid. We also argue that a compensation rate for excess clean energy can be an effective policy to promote energy independence (i.e., higher share of consumption of energy coming from the DRER owner's onsite energy). Our analysis sheds light to the growing literature on prosumer behavior.

The model presented in this study has several policy implications. First, the study suggests that there is a need for designing customized policy interventions based on how DRER owners view carbon emissions. Depending on the extent to which a community cares about their energy carbon footprint, policymakers could consider different levels of intervention. Related to this, the results indicate that there are potentially two types of proactive DRER owners with different views on their carbon footprint, leading to different optimal rates of self-consumption and onsite production. This suggests that policy interventions might need to be tailored to the preferences and behavior of different DRER owner groups. Second, to achieve a smooth energy transition, policymakers could benefit from understanding the level of disutility or preference for reducing energy carbon footprints within a community. If a community cares enough about their energy carbon footprint, active policy intervention may not be needed, as proactive DRER owners are willing to consume a large portion of their own energy produced onsite. Overall, the framework presented in the study can serve as a foundation based on which future studies can empirical examine to what extent and in what scenarios policies can be designed to take into account the attitudes of DRER owners toward carbon emissions and energy consumption patterns.

In the context of GCC, adopting the DRER model can help the nations to move toward a more decentralized and decarbonized energy system. It can also align with their specific regional context and energy needs, contributing to their broader goals of sustainability and climate change mitigation. However, it is important to note that the successful implementation of this model would require supportive policies and incentives, as well as a shift in consumer behavior toward more proactive energy management.

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Appendix

Solutions When Self-Consumption Rate Is Exogenous and Endogenous

Benchmark Case: Exogenous Self-Consumption Rate

We first characterize the equilibrium and derive closed-form solutions in the presence of disutility from carbon emissions, s. In the first stage, the prosumer maximizes Eq. (1) by choosing D_c and D_f subject to the budget constraint $M = P_c D_c + P_f D_f - (1-\gamma)P_b \phi D$. So,

$$\max \mathcal{L} = U(D_c, D_f) + \lambda \left(M - P_c D_c - P_f D_f + (1-\gamma)P_b \phi D - q_o\right)$$

whence

$$a_c - \beta_c D_c - dD_f + sE\left(1 + \frac{\phi}{1-\phi\gamma}\right) = P_c + P_b(1-\gamma)\partial q/\partial D_c$$

$$\begin{aligned} a_f - \beta_f D_f - dD_c - sE\left(1 - \frac{\phi}{1-\phi\gamma}\right) &= P_f + P_b(1-\gamma)\partial q/\partial D_f \\ M - P_c D_c - P_f D_f + (1-\gamma)P_b\phi D - q_o &= 0 \\ 1 &= \lambda \end{aligned}$$

where $D = (D_c + D_f)/(1 - \gamma\phi)$, $q = \phi D$, and

$$E = D_f - D_c - q = D_f\left(1 - \frac{\phi}{1-\phi\gamma}\right) - D_c\left(1 + \frac{\phi}{1-\phi\gamma}\right)$$

Hence, closed-form expressions for D_c and D_f are given by

$$\begin{aligned} HD_c = &\left(a_c - P_c + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[\beta_f + s\left(1 - \frac{\phi}{1-\phi\gamma}\right)^2\right] \\ &-\left(a_f - P_f + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[d - s\left(1 - \left(\frac{\phi}{1-\phi\gamma}\right)^2\right)\right] \end{aligned} \tag{6}$$

$$\begin{aligned} HD_f = &\left(a_f - P_f + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[\beta_c + s\left(1 - \frac{\phi}{1-\phi\gamma}\right)^2\right] \\ &-\left(a_c - P_c + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[d - s\left(1 - \left(\frac{\phi}{1-\phi\gamma}\right)^2\right)\right] \end{aligned} \tag{7}$$

where $H > 0$ is the determinant of the coefficient matrix of the system.

Next, we use these values for D_c and D_f and maximize the net revenue function given in Eq. (2), where the first-order condition is given by

$$P_b(1-\gamma)(1-\gamma\phi) = \phi(D_c + D_f) \tag{8}$$

whence we obtain the equilibrium renewable generation as a share of demand, $\phi^*(\gamma, s, P_C, P_f, P_b)$.

Substituting back this expression into (6) and (7) yields $D_c^*(\gamma, s, P_c, P_f, P_b)$ and $D_f^*(\gamma, s, P_c, P_f, P_b)$.

Next, differentiation of (8) gives

$$\frac{d\phi}{d\gamma} = \frac{\phi\left[\frac{\partial D_c}{\partial\gamma} + \frac{\partial D_f}{\partial\gamma}\right] + P_b\left[(1-\gamma)\phi + (1-\phi\gamma)\right]}{-P_b(1-\gamma)\gamma - D_c - D_f} \tag{9}$$

This expression gives Fig. 2 when $s = 0$. This is consistent with Fikru and Gautier (2023)'s nonlinear relationship between ϕ^* and γ when $s = 0$.

Endogenous or Optimal Self-Consumption Rate

We differentiate equation (1) with respect to γ and set it equal to zero; this characterizes the γ which maximizes utility, γ^u:

$$\begin{aligned}\frac{dU}{d\gamma} = 0 \Rightarrow &\left(P_c - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\frac{\partial D_c}{\partial\gamma}\\ &+ \left(P_f - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\frac{\partial D_f}{\partial\gamma}\\ &= -sE\frac{\phi^2}{1-\phi\gamma}D\end{aligned} \tag{10}$$

Substituting (10) into (9) gives

$$\rho\frac{d\phi}{d\gamma} = \phi\left[\frac{\partial D_f}{\partial\gamma}\left(1-\tilde{P}_f/\tilde{P}_c\right) - sE\frac{\phi^2}{1-\phi\gamma}D\right] + P_b\left[(1-\gamma)\phi + (1-\phi\gamma)\right] \tag{11}$$

where $\rho = -P_b(1-\gamma)\gamma - D_c - D_f < 0$, $\tilde{P}_f = P_f - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)} > 0$,$\tilde{P}_c = P_c - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)} > 0$. And $\tilde{P}_c > \tilde{P}_f$. Then, the comparative statics give

$$\frac{\partial D_f}{\partial\gamma} = s\left[\left(1+\frac{\phi}{(1-\phi\gamma)}\right)\frac{\partial E}{\partial\gamma} + E\frac{\phi^2}{(1-\phi\gamma)^2}\right] - P_b\frac{\phi(1-\gamma)}{(1-\phi\gamma)^2} \tag{12}$$

Substituting (12) into (11) and collecting terms and simplifying give

$$\begin{aligned}\rho\frac{d\phi}{d\gamma} &= s\left[\left(\frac{\phi}{\eta}\left(1+\frac{\phi}{1-\gamma\phi}\right)\frac{\partial E}{\partial\gamma} + \frac{E\phi^3}{(1-\gamma\phi)^2\eta}\right)\frac{\tilde{P}_c - \tilde{P}_f}{\tilde{P}_c} - \frac{E\phi^3 D}{(1-\gamma\phi)\tilde{P}_c}\right]\\ &\quad -\frac{\phi^2 P_b(1-\phi)\left(1-\tilde{P}_f/\tilde{P}_c\right)}{\eta(1-\gamma\phi)^2} + P_b\left((1-\gamma)\phi + (1-\gamma\phi)\right)\\ &= \frac{E\theta_1}{\gamma}\left(\epsilon_{e_\gamma} + \alpha\right) - \frac{\phi^2 P_b(1-\phi)\left(1-\tilde{P}_f/\tilde{P}_c\right)}{\eta(1-\gamma\phi)^2} + P_b\left((1-\gamma)\phi + (1-\gamma\phi)\right)\end{aligned} \tag{13}$$

where

$$\epsilon_{e_\gamma} = \frac{\partial E}{\partial\gamma}\frac{\gamma}{E} < 0$$

$$
\begin{aligned}
\frac{\partial E}{\partial \gamma} &= -\frac{\phi^2}{(1-\gamma\phi)}D + \frac{\partial D_f}{\partial \gamma} - \frac{\partial D_c}{\partial \gamma} - \left(\frac{\phi}{1-\gamma\phi}\right)\left(\frac{\partial D_f}{\partial \gamma} - \frac{\partial D_c}{\partial \gamma}\right) < 0 \\
\alpha &= \theta_1/\theta_2 > 0 \\
\theta_1 &= \Psi \frac{\tilde{P}_c - \tilde{P}_f}{\tilde{P}_c} + \frac{E\phi}{\tilde{P}_c} > 0 \\
\theta_2 &= \frac{\phi^3}{(1-\gamma\phi)^2\eta}\frac{\tilde{P}_c - \tilde{P}_f}{\tilde{P}_c} > 0
\end{aligned}
$$

Next, from (13), we obtain

$$
\begin{aligned}
&\rho\frac{d\phi}{d\gamma} = 0 \Leftrightarrow s = \frac{-P_b\left((1-\gamma)\phi + (1-\gamma\phi)\right) + \frac{\phi^2 P_b(1-\phi)}{\eta(1-\gamma\phi)^2}}{\frac{E\theta_1}{\gamma}\left(\epsilon_{e_\gamma} + \alpha\right)} = \bar{s} \\
&\rho\frac{d\phi}{d\gamma} < 0 \Leftrightarrow s > \bar{s} \\
&\rho\frac{d\phi}{d\gamma} > 0 \Leftrightarrow s < \bar{s}
\end{aligned}
$$

where $\rho < 0$.

The Effects of s on γ^u

Consider the expression for total demand, $(1-\gamma^u\phi)D = D_f + D_c$, where in equilibrium γ^u, D, D_f and D_c are functions of s. Differentiating (dropping the $*$ superscript) and imposing the no rebound effect assumption ($dD = 0$) gives

$$
0 = \frac{dD_f}{ds} + \frac{dD_c}{ds} + \phi D\frac{d\gamma^u}{ds} + D\gamma^u\frac{d\phi}{ds} \tag{14}
$$

where the first and second terms are negative and positive, respectively. That is, an increase in s induces the prosumer to decrease (increase) default (clean) energy from the grid to reduce emissions and thus the disutility from emissions. The fourth term is positive: An increase in s prompts additional energy production onsite by the prosumer.

Next, consider

$$
\frac{dD_f}{ds} + \frac{dD_c}{ds} < 0 \Leftrightarrow s > \tilde{s}^* \tag{15}
$$

That is, the reduction in default energy consumption and the associated increase in clean energy consumption from the grid leave room to the prosumer to raise own energy consumption as long as the prosumer's disutility from emissions is large enough. In this case the prosumer is willing to raise her own energy consumption, γ^u, to address the higher disutility from emissions. In the context of (14), this means that the sum of the first, second, and fourth terms is negative and, therefore, the third term must be positive ($d\gamma^u/ds > 0$) for (14) to hold. A similar logic applies to the case of small disutility from pollution, $s < \tilde{s}^*$.

From (15) we have

$$\begin{aligned}\frac{dD_f}{ds} + \frac{dD_c}{ds} &= \mu_1 - \mu_2(D_f + D_c) - \frac{2(D_f + D_c)\phi^3}{(1-\gamma\phi)^3}s \\ &< 0 \Leftrightarrow s > \frac{\mu_1 - \mu_2(D_f + D_c)}{\frac{2(D_f+D_c)\phi^3}{(1-\gamma\phi)^3}} \end{aligned} \tag{16}$$

where

$$\begin{aligned}\tilde{s}^* &= \frac{\mu_1 - \mu_2(D_f + D_c)}{\frac{2(D_f+D_c)\phi^3}{(1-\gamma\phi)^3}} \\ \mu_1 &= 2(a_c - \eta_c)\left(1 - \frac{\phi}{1-\gamma\phi}\right) + (a_f - \eta_f)\left(1 + \frac{\phi}{1-\gamma\phi}\right) \\ \mu_2 &= \beta_c\left(1 - \frac{\phi}{1-\gamma\phi}\right)^2 + 2d\beta_f\left(1 + \frac{\phi}{1-\gamma\phi}\right)^2 \\ \eta_c &= \eta_f = P_b(1-\gamma)\frac{\phi}{1-\gamma\phi}\end{aligned} \tag{17}$$

The Effects of P_b on ϕ and γ^u, and Role of s

From (6) and (7) we obtain

$$\frac{\partial D_f}{\partial P_b} = \frac{(1-\gamma)\phi}{(1-\gamma\phi)}\left[\beta_c - d + 2s\left(1 - \frac{\phi}{(1-\gamma\phi)}\right)\right] > 0 \tag{18}$$

$$\frac{\partial D_c}{\partial P_b} = \frac{(1-\gamma)\phi}{(1-\gamma\phi)}\left[\beta_f - d + 2s\left(1 - \frac{\phi}{(1-\gamma\phi)}\right)\right] > 0 \tag{19}$$

where $\beta_c > \beta_f$ means that the increase in default energy is greater than the increase in clean energy from the grid.

Consider total energy demand $(1 - \gamma^u\phi)D = D_f + D_c$ in equilibrium, where differentiation and imposing the no rebound effect assumption ($dD = 0$) give

$$0 = \frac{dD_f}{dP_b} + \frac{dD_c}{dP_b} + D\gamma^u\frac{d\phi}{dP_b} + \phi D\frac{d\gamma^u}{dP_b} \tag{20}$$

where the first three terms are positive since an increase in the compensation rate prompts the prosumer to increase energy production onsite, which generates additional income and thus demand from the grid (default and clean). As a result, in the absence of the rebound effect (20) suggests that the fourth term is negative meaning the prosumer lowers her consumption of own energy since now she is consuming more the grid.

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