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Solar PV generation in Colombia - A qualitative and quantitative approach to analyze the potential of solar energy market

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A B S T R A C T

Colombia faces several challenges to secure a reliable, affordable, and climate-friendly energy supply. Persistently low reserve-to-production ratios in oil and gas, together with advancing climate change, are putting the country's energy system at risk. Heavily relying on hydro-power, Colombia's electricity system will become more vulnerable with extreme weather patterns such as El Niño. This paper offers a multi-method study of the role of photovoltaic (PV), specially prosumage systems, to support a slowly starting energy transition in Colombia. First, qualitative data from an expert elicitation in Colombia's energy sector is analysed. Second, a model to calculate the internal rate of revenue for households is used to identify optimal sizes for household PV or prosumage systems under the new regulatory framework. Key concerns emerging from the expert elicitation include lacking substantial financial aid, insufficient tax incentives, and high equipment prices, which raise investment and operation costs. Also, model results confirm net-metering implementation as an enabler of widespread deployment of household PV systems. Most profitable system configurations include PV systems without storage technology. Our findings show that financial instruments are still insufficient to scale-up household level PV deployment.

1. Introduction

Colombia's energy system is on the verge of experiencing groundbreaking shifts. Non-hydro renewable energy sources (RES), mainly solar and wind energy promise to play a central role in this incoming transformation due to their contribution to providing a resilient, reliable, affordable and clean energy system [1–4]. Nevertheless, their role and enhanced deployment is by no means certain. Ongoing energy planning still aims to increase the share of coal- and gas-fired generation; ongoing fossil-based projects would more than double fossil-based power generation by the end of the decade [3–6]. At the same time Photovoltaic (PV) and wind energy are facing many barriers to be deployed at large scale [7,8], and only represent a puny 0.10% of installed capacity in 2018 [9].

This paper aims to offer a context-based analysis of the potential of household-level PV solar generation and how the country can benefit from the worldwide trend of the increasing use of renewable energy technologies and their improvement in performance, efficiency and cost-competitiveness [2,10]. Besides providing a holistic view of key contextual variables of Colombia's energy system, an objective in this article is to examine whether PV and prosumage[1] are a profitable option for Colombian households. A final objective of our research is to provide useful insights on the effectiveness of the renewable energy sources (RES) support instruments that began to be implemented after the enactment in 2014 of the 1715 (Unconventional Renewable Energies Law). To achieve these objectives, we combine qualitative and quantitative methods to investigate the potential of household level PV systems. After providing an introduction to Colombia's energy policy context, a qualitative analysis of an expert elicitation is carried out.

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[1] The term prosumer describes an energy consumer producing electric energy and feeding it into the grid. Prosumage, on the other hand, describes a system also able to store electrical energy in addition to consuming and producing it [11].

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Afterwards, the internal rates of revenue for household PV systems are modelled to identify optimal configurations for household PV deployment. These approaches aim to answer the study's underlying research question: *"Are small-scale PV or prosumage systems for households profitable under the current regulatory framework of Colombia"*. Finally, results are presented, discussed and conclusions drawn.

Decentralized technologies have gained relevance worldwide and paved the way for prosumers and prosumption. Prosumption and prosumage may be particularly interesting for low-consumption households and systems, for example in off-grid areas, such as Colombia's Non-interconnected Zones (ZNI) [12]. Such innovations depict a societal shift towards multilateral economic interactions driven by information and new technologies [11]. As Green et al. [13] show with their analyses on prosumage systems in the UK, the primary goal of prosumage is not energy autarky but rather a tool to increase and optimize a household's consumption and save money. As will be discussed, PV-based prosumage systems hold a variety of advantages for Colombia's energy transition.

Concerning Colombia's energy policy context, it is key to highlight that RES and especially PV play a fourfold role in transitioning towards the energy system of the future.

First, non-hydro RES have the potential to increase the resilience of Colombia's hydro-heavy power system [3,14,15]. Hydro power generated more than 77% of electricity according to the latest figures of 2018, while other RES accounted for 0.10% [9]. This has followed a regional trend in Latin America, which has neglected diversification efforts and privileged hydro-power [16]. Meanwhile, advancing climate change is increasing the vulnerability of the country's power system [14]. In Colombia, extreme climatic events such as the El Niño Southern Oscillation (ENSO), cause drastic reductions in precipitation levels, which put water reservoirs at strain [17,18]. Research suggests increasing global temperatures resulting from global warming, will increase the frequency of extreme El Niño Southern Oscillation (ENSO) events [19,20]. At the same time, government research suggests that wind energy and PV solar can effectively complement hydro generation in up to 90% of the time when precipitations are insufficient, according to the high RES deployment scenario of the government's Mining and Energy Planning Unit (UPME). In such a scenario, the wind and solar share would increase from 0.10% to 16.7% of installed capacity [3]. Furthermore, optimization exercises have concluded that "Hydrothermal power (i.e., hydro, gas and coal) are almost never part of the optimal expansion plans identified within the analysed scenarios, except when environmental pollution costs are ignored" [15]. At the same time, the results in Ref. [15] suggest that 100% of additional capacity should come from non-hydro RES, thus increasing wind and solar share in power generation up to 60% of total capacity in 2030. This would be cheaper in the long run and would increase the power system's climate resilience, compared to maintaining the current hydro-heavy, coal, and gas supported generation park [15]. A final argument regarding energy security, concerns the fact that climate change not only affects hydro power, since conventional power plants need cooling water to function [21]. With shrinking levels of water availability as climate change advances, in many regions thermal power plants can end up becoming a liability and not an asset in terms of reliability [22].

Second, the deployment of non-hydro RES, and especially PV, offers a perspective beyond Colombia's current energy policy and planning. For the past decades, the focus has been placed on promoting foreign income generation via energy exports, mainly through hydrocarbon and coal exports [23]. Consequently, other key areas such as energy system resilience or energy access have been neglected [23]. Concerning energy access, Colombia produced more than four times its domestic total final consumption of energy in 2016 [24], while "approximately ten million of Colombian citizens have no access to electricity in a daily basis" [23]. As for resilience and diversification, Colombia has not done much to diversify its energy matrix. It has considerably lagged in deploying other renewable alternatives such as solar or wind power [7,25], and with the downturn of oil and coal prices has increasingly faced economic problems [5,26].

Third, ongoing efforts to diversify the electricity matrix, expand energy access and increase the power system's resilience are betting on large-scale coal and gas power plants to do so. The National Energy Plan for 2050 expects doubling the share of coal-fired generation to 12.5% of installed capacity by 2028 [27], while the latest Generation-Transmission Expansion Plan expects coal to deliver over 18.5% of power by 2031 [3]. Currently, there are 1,575 MW in Colombia's coal pipeline, enough to double the country's capacity [6]. These additions would trump any efforts to decarbonize Colombia's energy system and reduce Green House Gas (GHG) emissions [5,28]. As [15] shows, this is not only unnecessary but inefficient and costlier than deploying RES instead.

Fourth, the ongoing global energy transition is already showing that distributed wind and solar energy will play a central role in transitioning away from fossil fuels and securing a reliable, affordable and clean energy supply [1,29]. According to ongoing research, Colombia "is rated as one of the best countries in South America for generating electricity from wind energy" [7] and could cover its whole domestic energy demand by using only half of its technical potential [30]. Increasing research also highlights that PV will play a definitive role due to its versatility [12,31], its scalability [25] and its complementarity with existing hydro generation [3,14,15]. Furthermore, due to Colombia's relative small per capita energy consumption, a transition towards RES could occur much faster than elsewhere [32]. Colombia's energy use per capita was 0.7 toe, compared for example with 1.5 toe, 2.7 toe or 3.8 toe in Mexico, South Africa or Germany, respectively [33]. Furthermore, the six largest consumers of electricity, comprising over 5% of overall demand, are all in the fossil extraction sector [3], which will have to be eventually phased out [34]. Meanwhile, 41.71% of national per capita power demand stems from the residential sector [3] and up to 70% of power demand stems from small "regulated" users, mostly comprised of private households [35,36].

This context suggests that considering Colombia's energy demand and demand structure, it may have an easier transition pathway than other high-consumption countries. It also suggests that households will play a central role in the energy transition. Therefore, we continue the analysis by focusing on the conditions under which PV-based prosumage systems can operate in Colombia, and how prosumage and PV deployment have been promoted in Colombia and elsewhere.

The literature discussing policies to support the expansion of RES has been growing in the past years. While considerable research has focused on Europe's different support schemes [37–39], other pieces discuss renewables support from a more global perspective. From general analyses [40,41], going to pieces with a focus on key global players such as China or Australia [42], Brazil [43] and South America [44].

Among the reasons that several studies give to justify the support for renewables, the high upfront capital costs of RES-investments are paramount [45]. Since RES do not pay fuel costs, most capital costs have to be incurred at the beginning of a project's lifetime. This makes RES more sensitive to financial costs than conventional energy sources [46]. Therefore, addressing the risks involved in sourcing the necessary capital to carry out investments is key. This is especially true for countries such as Colombia, where diverse kinds of risk increase the costs for financial capital [47,48].

To deal with this, there is a wide range of policy instruments that can be implemented to support RES. These include production support schemes such as feed-in tariffs (FITs), feed-in premiums (FIP) or renewable portfolio standards (RPS). Amongst the investment support schemes, investment tax credits (ITC), grants or other kinds of fiscal instruments (e.g. different kinds of tax rebates, accelerated depreciation, etc.) can be taken into account. As one study focusing on Europe concludes, a significant portion of countries implement both production and investment based support policies to complement one another [38].

For the situation in Colombia, recent studies looked at the impacts of existing policy instruments for RES deployment. The most important of them is the 1715 law of 2014, which is Colombia's main RES legislation, and which is being currently implemented. Radomes and Arango [49] discuss support policies for PV expansion at municipal level in Medellín. Rodríguez-Urrego [25] take stock of the level of PV deployment in Colombia, as well as some of the policies that have enabled it. On a more critical tone, Jimenez, Franco, and Dyner [8] criticize the lack of ambition in current RES support schemes and call upon the government to engage in more ambitious actions to support an extensive deployment of RES.

Another strand of literature focuses on off-grid solutions and the role of RES in the provision of distributed electricity generation and increased electricity access in off-grid regions. According to one study focusing on Nigeria and Ethiopia, depending on the population density and income levels of different regions, RES and especially PV offer an affordable and zero-carbon alternative to extend electricity access via grid extension, the construction of micro-grids and off-grid solutions, respectively [50]. Furthermore, Szabó et al. show in their study on Sub-Saharan Africa that PV is already an option to leapfrog fossil-fuel intensive electrification [51]. As their analysis shows, in just four years (2008–2012), PV replaced diesel as the cheapest alternative to extend electricity access in remote areas. For Colombia, Mamaghani et al. [12] analyze the potential of different PV, wind and diesel combinations to extend electricity access in remote off-grid areas in Chocó, La Guajira and Boyacá. They conclude that entirely renewable configurations are the most preferred from an environmental and long-run economic perspective. Nevertheless, due to initial high capital investments, these configurations may not be invested on. Other studies also come to similar conclusions in different Colombian locations [31,52,53].

Concerning PV in particular, Castañeda et al. [54] assess the effect of FIT, net metering, and capital subsidies on household-level PV deployment. Leon-Vargas et al. [53] conduct a pre-feasibility study on household level wind and solar energy deployment in Bogotá, amongst other cities. Cardenas et al. [55] looks at the possibilities and impacts of rooftop solar deployment in Colombian households.

Providing a comprehensive analysis of all RES technologies in all Colombian regions is nevertheless beyond the scope of this paper. Therefore, the focus is set on PV and the modelling is conducted for three Colombian regions (Bogotá, Barranquilla and La Guajira).[2]

As the cited pieces show, there are plenty of simulations looking at a variety of indicators such as return ratios or payback time [53], installed PV capacity, cost of investments or average Levelized Cost of Electricity (LCOE) [56], share of PV in generation [55], amongst others. Some studies also look at regulatory variables and qualitative information [8,23,57,58]. Nevertheless, interdisciplinary and multi-method studies explicitly drawing from qualitative information from experts, while also conducting own simulations and thus offering a holistic, interdisciplinary perspective, are seldom. This is the research gap that the present multi-method study aims to fill.

With this in mind, the starting point for the increasing relevance of PV in expanding electricity access and reducing GHG emissions has been the drop in generation, installation and financing costs of RES technologies. Latest reports on the cost of PV state, by taking a LCOE approach, that this technology is already highly competitive with most conventional energy sources [1]. Moreover, looking at a life-cycle assessment of different technologies, PV comes up as the most climate friendly technology [59]. Coal, Colombia's other dominating energy source besides hydro-power, on the other hand, becomes one of the most expensive ones, once all its negative effects (e.g. air, water and soil pollution, GHG emissions, etc.) are taken into account [60].

Due to the structure of Colombia's electricity system (e.g. where electricity tariffs are cross-subsidized), the existing gap in financing energy supply to poorer households also has to be analysed further, as it offers many possibilities and challenges in the context of potential prosumage policies. Here, existing research has discussed the implications of "grid defection" [61]. While the cited study, which focuses on the USA, is not dismayed by the potential negative effects of this phenomenon, the highly context-specific nature of Colombia's cross-subsizing scheme may warrant more caution. As Monyei et al. [62] discuss, the introduction and expansion of RES will not, by itself, lead to a sustainable energy transition. Special care has to be taken, so that a transition does not lead to an unfair sharing of the burden of transition and to energy poverty.

2. Current status-quo in Colombia

As the third largest Latin American economy and home of important fossil fuel reserves, Colombia's energy future is not only relevant at a domestic level, but can have global consequences. For example, if the country were to extract its steam coal reserves, either for exports or for internal consumption,[3] the global carbon budget would be reduced by 17.42 Gt CO_2eq (which correspond to nearly half of annual global emissions or 4% of the remaining carbon budget to stay below 1.5 °C). Hence, determining whether PV and prosumage offer a viable alternative to a carbon-intensive development path, is paramount.

With the aim of examining whether under the current circumstances PV and prosumage are a profitable option for Colombian households, as well as to provide useful insights on the effectiveness of the RES support instruments enacted by the Colombian government, the current situation in Colombia regarding the electricity market and the regulatory framework is discussed.

2.1. Electricity market

With regards to energy distribution on a local level, Colombia has unique features. Like other public services, electricity is distributed according to a stratified system which is divided into six strata or sectors. Sectors 1–3 are associated with households in lower income areas and 5–6 with households in higher income areas of the cities [63]. Hence, the stratification is bound to

[2] PV as primary technology was chosen on the basis of its singular role in allowing households to engage in multilateral economic relations. The areas of study were chosen due to their centrality (Bogotá), their closeness to ports and industrial hubs (Barranquilla) and the current low level of grid-based electricity provision (La Guajira). For more detail on case selection, refer to section 3.3.

[3] There is a growing concern that this could become a possibility. Furthermore, several of the interviewed experts confirm the Colombian government's intention to use as much coal as possible.

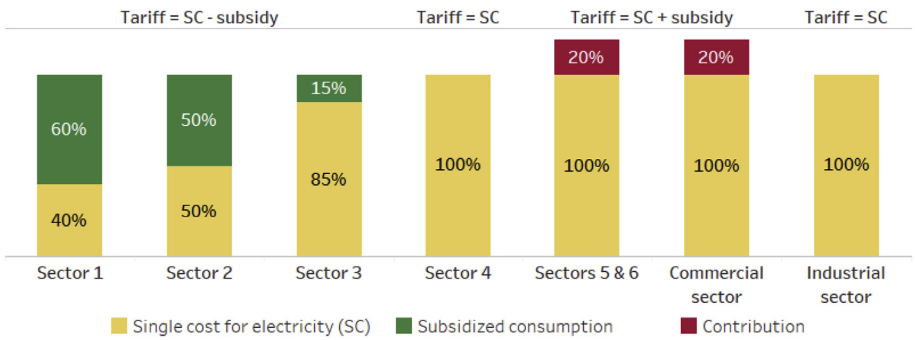


Fig. 1. Overview of electricity tariffs and sectors.
Source: Own illustration based and modified from Ref. [63].

property, but not household income, and electricity prices per kWh thus look different for households located in neighborhoods associated to different strata −regardless of consumption [64]. According to this cross-subsidy, the latter sectors subsidize the 1-3 sectors by paying 20% more on electricity. Sector 4 stands for middle-class areas and is not subsidized. Fig. 1 gives an overview of the sectors and the corresponding tariffs. Since households in sectors 5–6 are by definition associated with higher levels of affluence, we assume that these households will have more capital to invest in the installation of PV systems. Furthermore, due to them paying the highest electricity tariffs from all six sectors, we assume that sectors 5 and 6 could benefit most from feeding into the electricity grid. Basing on these two assumptions, sectors 5 and 6 are chosen for the calculations of the prosumage model.

Since the residential sector currently makes up for around 42% of per capita electricity consumption in Colombia [3,35,36], we restrain from further looking into the potential of PV or prosumage for the industrial sector. Note only that, as can be seen in Fig. 1, the industry is not subsidized.

The tariffs shown in Fig. 1 are applicable only to Colombia's National Interconnected System (SIN). In Non-interconnected Zones (ZNI), small and private electricity grids, as well as a significant dependency on diesel generators have resulted in high electricity prices, poor coverage and low reliability in electricity supply. In turn, this has led to an increasing number of projects for the use of unconventional renewable energies [65,66].

2.2. Photovoltaic in Colombia

Geographical and weather conditions are inherently important for variable RES like PV systems. Countries near the equator, such as Colombia, have a higher average solar radiation than most countries in Europe or the United States. As one can see in the right hand of Fig. 2, the Guajira peninsula in the north-east and the Orinoco flatlands in the east of Colombia reach the highest national values at 6.0 kWh/m.[2] To compare, this is as much as some areas in Southern California or the Northern Sahara.[4] The left hand of Fig. 2 illustrates that these are also those regions that are isolated from the National Interconnected System (SIN).

Contradictory studies taking stock of Colombia's PV potential estimated that only 5.28–104 MW capacity were in place at the beginning of the year 2017 in the ZNI and SIN areas [25,69].[5] To compare, the neighboring Peru had at least twice the installed capacity of PV with 201 MW [69], while Chile's PV capacity is expected to have surpassed 2,000 MW in 2018.[6] In the ZNI areas, total generation capacity in 2015 was estimated to be 165 MW, accounting for 1% of the overall installed capacity of PV in Colombia [70]. The involvement by the Institute for Planning and Promotion of Energy Solutions in Non-Interconnected Zones (IPSE) has contributed to raise the installed capacity of PV in off-grid areas to almost 2.5 MW [25]. Still, solar PV plays a minor role in both grid and off-grid areas in Colombia.

First steps to integrate utility-size PV are being taken. The Yumbo solar park, with around 10 MW_p, was put into operation in 2017 in the region of Valle del Cauca.[7] More recently, an 86 MW solar park was inaugurated.[8] If the more optimistic numbers on PV deployment (compare [69]) are added to the capacity of the previous examples, Colombia will have already surpassed 200 MW of installed PV by the end of 2018.

Solar projects continue to gather pace, and an increased deployment at household and utility size can be expected for 2019.[9] Regarding the current structure of the solar energy market in Colombia, it is characterized by a variety of small companies and start ups which have started to offer their services over the past few years,[10] competing with larger companies such as EPM, Celsia or ENEL. Even though not much data on the market is available, the information gathered from expert interviews allows to conclude that at least the utility-size market is concentrated in few players. While this is not negative per se, the past years of solar industry development show that competition has been a key factor for cost reductions in both PV production and installation in other countries [71].

2.3. Overview of the regulatory framework

The 1715/2014 law (Unconventional Renewable Energies Law) was designed to promote and support investment in RES, especially through tax incentives and declaring the integration of renewable energies in the national electricity mix. Its primarily goals were to supply remote areas with electricity, but also to explore the overall potential of unconventional RES. Additionally, the law foresaw a regulation for the feed-in of surplus electricity and the creation of a fund for investments in RES and efficient energy management (in

[4] https://globalsolaratlas.info, last accessed: 8.5.2019.
[5] Out of in total 16853 MW generation capacity for Colombia [9].
[6] https://www.pv-magazine.com/2018/02/05/chiles-pv-capacity-surpasses-2-gw/, last accessed: 8.05.2019.
[7] http://www.celsia.com/granjas-solares, last access 25.07.2018.
[8] See for example: https://www.elespectador.com/economia/se-fortalece-la-energia-solar-en-colombia-articulo-849271, last access 09.04.2019.
[9] See for example: http://www.celsia.com/es/energia-solar, last access 07.11.2018.
[10] See for example: https://www.portafolio.co/economia/finanzas/es-buen-negocio-generar-su-propia-electricidad-523125, last access 08.11.2018.

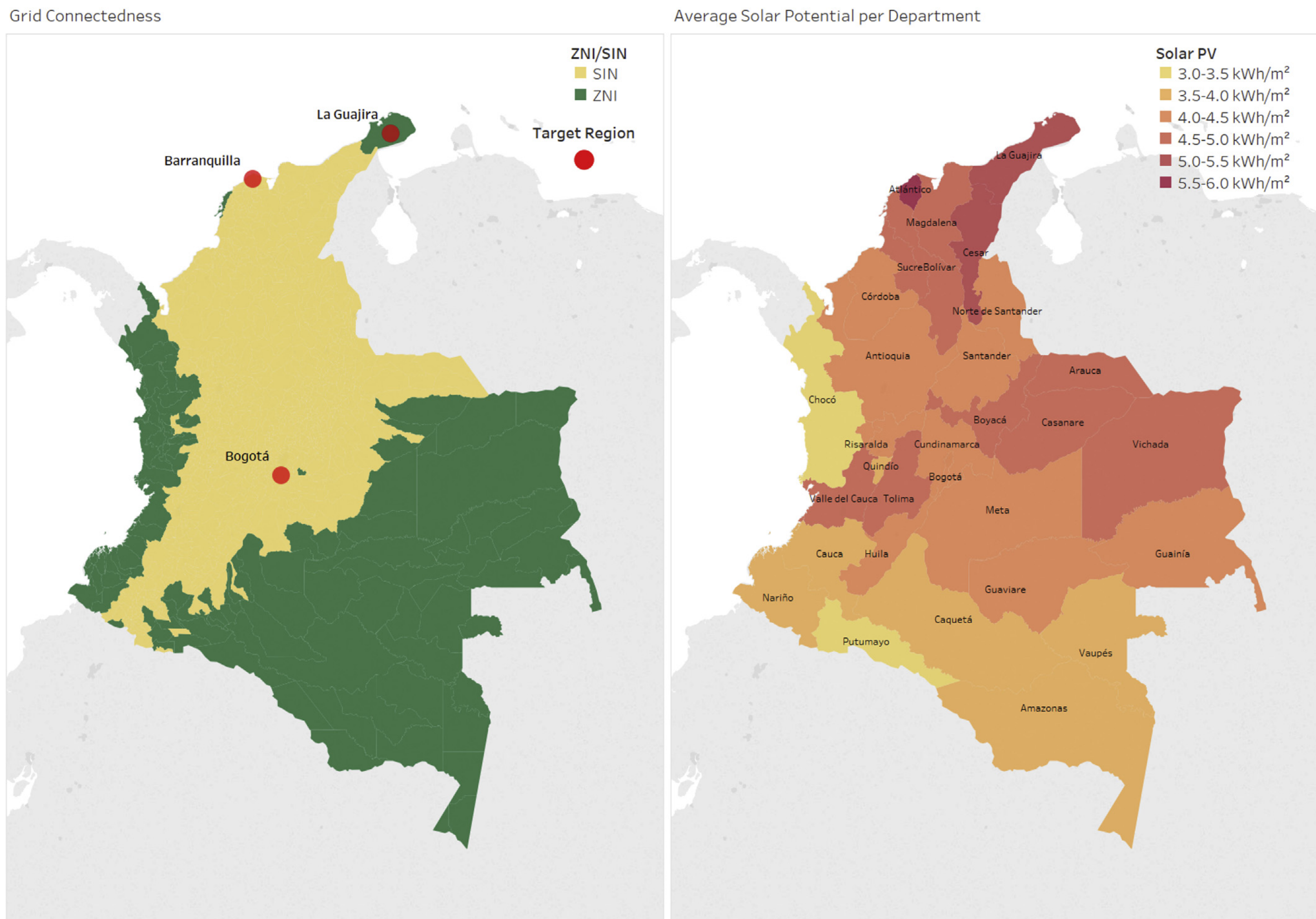


Fig. 2. Map of Colombia with regions connected to the grid (SIN) and off-grid regions (ZNI) (left figure), and average daily solar irradiation per department (right figure). Source: Own illustration based on [67,68].

Spanish: Fondo de Energías Renovables y Gestión Eficiente de la Energía - FENOGE) [65]. Chapter III of the 1715 law further defined the incentives and financial instruments promoting the electricity generation with renewable energy technologies [65,72].

As the law was being implemented, the Ministry of Mines and Energy (MME) issued the decree 348/2017, which defined what kind of small-scale RES-projects are to be supported and how. It regulates the procedure to obtain the benefits foreseen by the law 1715/2014 and especially of the resolution 045/2016 issued by the Energy-Mining Planning Unit (UPME).[11] The aim of all these regulations is to ease the process of grid-connection for power plants and the regulation for selling surplus electricity integrating the installation of renewable energy and solar power systems for self-consumption considering systems up to 100 kW_p. This includes exemption of the value-added tax (VAT) on machinery, equipment, and labor costs. Additional tax incentives were given with a special reduction of income tax (maximum amount to be deducted: 50% of the total investment costs within 5 years) and exemption of the duty tax (import tariff) on machinery, equipment, and materials that are not produced in Colombia. Furthermore, the yearly depreciation rate was increased by up to 20%. The implementation of net-metering to receive energy credits for the surplus electricity fed into the grid is regulated in the resolution 030/2018 issued by the Colombia's Energy and Gas Regulatory Commission (CREG). In it, the conditions to join the grid, the maximum participation of distributed generation in total load (both at nodal, regional and national levels), as well as the technical aspects of grid connection for PV systems is outlined.

Looking at the current policy developments, it can be concluded that the Colombian government has opted for a mix of investment and to a lesser extent production based RES support. As the results of the expert elicitation will show, this has important implications for the profitability of RES projects.

Before the 1715 law of 2014, the previously existing legislation (laws 633 from 2000, 697 from 2001 and 788 from 2002) only restricted itself to rhetorically encouraging the deployment of RES, as well as reducing the tax burden on ethanol producers [73]. Hence, this study takes the established view in recent literature [25,31,52,54,58,74], in taking the 2014 legislation as the first true RES promotion policy in Colombia.

Fig. 3 gives an overview of selected regulatory laws and programs in Colombia concerning solar PV and other "unconventional" RES.

3. Methodology

To investigate the potential of PV and analyze more in depth how PV can be further expanded in Colombia, two different

[11] UPME resolution 045/2016 sets out the criteria according to which RES projects can be certified and become eligible for tax exemptions and government funding.

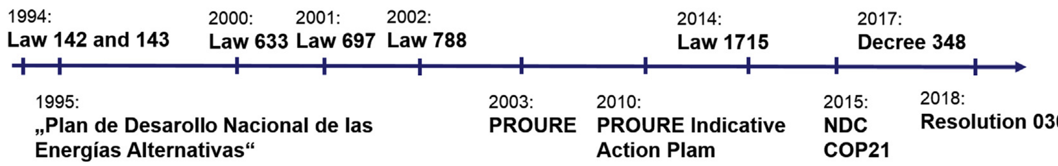


Fig. 3. Overview of selected regulatory laws and programs in Colombia.
Source: Own illustration based on [75–77] and Resolution 030/2018.

approaches are used. First, a qualitative approach is used to gather the perspectives of different actors and stakeholders in Colombia on the potential, necessary support and barriers of the broader implementation of PV. Furthermore, a quantitative approach tests whether these ideas are operatively within the current legal framework for PV for a prosumage systems. Using both methods makes it possible not only to enumerate a set of proposals but to get an idea of their actual impact.

3.1. Qualitative approach: expert elicitation

An expert elicitation is a qualitative empirical research method to elaborate on a specific topic or research question. The aim is to develop a deeper understanding of a particular question or a range of questions within a specific topic [78]. Here, the goal is to conduct a systematic expert elicitation to broaden the understanding of the RES' potential in Colombia. Moreover, the elicitation aims to evaluate certain target areas where solar PV should be implemented, the current problems and the necessary changes in the regulatory framework.

The expert elicitation was carried out over a period of three months in 2018 using an online survey tool.[12] The survey consisted of seven chapters, covering the general information of the expert, electricity production, renewable energy, solar PV, regulatory instruments, and investments in Colombia. The survey questions were asked in an open and predefined matter in order to create an overview and a discussion basis. Overall, 14 experts conducted the elicitation. The majority of the experts are working in industry or academic positions and others in politics and government. This selections of experts serves the purpose of the elicitation to gain a deeper insight into the Colombian energy sector concentrating on solar PV. To confirm the validity of research insights and include most recent developments, additional exploratory interviews were carried out in the aftermath of the expert elicitation in 2018 and 2019 in various locations of Colombia.

3.2. Quantitative approach: prosumage model

The prosumage model used in this analysis was created by Eissler et al. [79] and has already been used to evaluate business opportunities of prosumage systems for different locations, such as India or Germany. The model is split up into four separate modules, calculating production, consumption, investment costs, and the final Internal Rate of Return (IRR).

The objective of the model is to derive the cost-optimal size of battery installments depending on local temperature, solar radiation data, and regulatory conditions, such as net-metering and electricity prices. Detailed information on the data used to model Colombia can be found in the appendix.

The model was expanded in order to represent Colombia's net-metering regulation and tax incentives mentioned in chapter 2.3. Most notably, for obtaining the total electricity costs, the energy credits - *VE* (in Spanish: valor excedente) at the accounting period *f* given the month *m* and hour *h* have to be calculated. For the model expansion, the simplified formula[13] as seen in equation (1) has been used according to the regulatory framework.

$$VE_f = \left(Exp1_{f-1} - Imp_{f-1}\right) * CUv_m - \left[Exp1_{f-1} * Cv_m\right] + \sum_{h=hx,hx+1,\dots,H} Exp2_{h,f-1} * PB_{h,f-1} \quad (1)$$

When the surplus $Exp1_{f-1}$ is equal to or lower than the amount taken from the grid Imp_{f-1}, the difference in kWh is multiplied with the single cost of electricity CUv_m (see 1). The price for commercialization or "marketing price" Cv_m is then deducted, since the self consumed electricity is not sold to the electricity provider. Finally, the exceeding surplus is multiplied with the current energy stock exchange price $PB_{h,f-1}$.

From these different data points the model computes several metrics for different sizes of battery and PV systems including levelized costs of electricity (LCOE) and the Internal Rate of Return (IRR). The IRR is the discount rate when the Net Present Value (NPV) is set to zero [80] and its calculation is shown in equation (2). Usually, if the IRR is higher than the costs of capital the investment is profitable. For further information on the model and the underlying assumptions, see Ref. [79].

$$-Investment_{t_0} + \sum_{t=1}^{N} \frac{Income_t - Expenditure_t}{(IRR+1)^t} = 0 \quad (2)$$

3.3. Regional case selection

The difference between areas connected to the SIN and the ZNIs is investigated by looking at cities, such as Bogotá and Barranquilla, and the region of La Guajira. As one of the most important harbours of Colombia, Barranquilla's location keeps transportation costs of imported components for a potential stand-alone PV or prosumage installation low in comparison to Bogotá and La Guajira. In addition, due to the harbour and several free-trade agreements that have been signed over the past years, the region has experienced a considerable industrial development [81]. Therefore, the demand for electricity is high and the existence of an electricity grid makes net-metering scenarios possible in contrast to La Guajira. At the same time, the yearly solar irradiation conveniently lays at around 2045 kWh/m^2; nearly comparable to La Guajira (compare with section 2.2).[14] All these factors make Barranquilla very interesting for PV deployment. Bogotá has a slightly lower solar irradiation, but

[12] The survey was carried out before resolution 030/2018 was issued by the CREG and before the parliamentary and presidential elections in order to avoid politicized results.

[13] For further information see https://www.codensa.com.co/document/Resolucion-CREG-030-2018.pdf, last access 07.11.2018.

[14] https://solargis.com, last access 23.03.2018.

Table 1
Household devices included the model.

Fridge	ICT	Lighting	Home appliance
including freezer	Television, 3 telephones, 5 computers	10 active light bulbs	Washing machine, electric Stove

Table 2
Consumption of households with Colombian specific demand.

Application	Time ranges	Week/Weekend	Demand in W per day	Probability of usage per day	Activity in timerange
Freezer/Fridge	24 h	both	1440	1	constant
ICT	12:00–24:00	both	1485	0.8	constant
Lighting	06:00–08:00, 18:00–24:00	week	240	1	constant
Lighting	18:00–24:00	weekend	240	1	constant
Lighting	18:00–24:00	both	240	0.5	1 h
Stove	18:00–20:00	week	3000	1	1 h
Stove	12:00–16:00	weekend	3000	1	1 h
Washing Machine	08:00–10:00	both	1200	0.5	1 h
Oven	12:00–18:00	both	1200	0.25	1 h
Microwave	18:00–20:00	both	400	0.28	1 h
Vacuum cleaner	18:00–20:00	both	1400	0.14	1 h
Iron	14:00–17:00	weekend	1200	0.5	1 h
Hair Dryer	06:00–07:00	both	1780	0.07	1 h
Sound System	18:00–20:00	both	80	0.42	1 h

Source: Adopted with data from Ref. [79] and modified with Simulador Codensa.[16]

its mild weather can have a positive impact on the efficiency of PV panels. Since it is the capital city of Colombia, the concentration of households belonging to sectors 5 and 6 is high which makes it also an attractive location for PV and prosumage systems.

On the other hand, the off-grid region of La Guajira is characterized by decentralized power generation units, most of them using fossil fuels such as diesel, with poor distribution. In many cases, the local energy supply can only be used to cover the demand of municipal capitals. As a result, many communities are forced to use diesel generators to produce electricity at around 50 €/kWh [31,65] Despite large scale projects to exploit the wind potential in this area, the government has not issued any extension plan for the grid in La Guajira, nor distribution lines, but only for the transmission lines between the SIN and several wind parks in planning and approval processes possibly reaching up to 1.5 GW by 2022 and even 7 GW by 2030 [3,82].[15] Therefore, prosumage systems might represent an attractive and reliable option decentral.

3.4. Data

All scenarios are based on the same consumer behaviour, shown in Table 2, and corresponding to households from sectors 5 and 6, as stated in section 2.1. The simulated households do not consider heating or air conditioning and therefore the differences between the regions become less important. For further research heating and air conditioning could be included. The included devices for each household are presented in Table 1. Generally, due to the climate of these areas space-heating would likely not change the differences. Instead, including warm-water-heating and space-cooling could increase the energy demand in off-peak hours (morning, evening) and thus could give more incentives for storages.

4. Results

By using the combination of a qualitative and a quantitative approach to analyze the potential of PV and Prosumage in Colombia, we gain further and broader understanding of the research question and can combine these two approaches to a cohesive outlook.

4.1. Evaluation and analysis of expert elicitation

The results of the expert elicitation show an overall agreement regarding the need for more RES, especially solar energy, to diversify the energy mix in Colombia. According to the experts, a change could be beneficial, since Colombia could reduce its dependency on electricity generation from hydro-power and fossil fuels.

As depicted in Fig. 4, the responses show that policies are needed to increase PV in Colombia. This results in a lack of political incentives and not enough will and public interest. 86% of the respondents mentioned that to have a successful energy transition, more political incentives are needed since solar energy is still too expensive in Colombia, caused by expensive solar equipment and a lack of skilled labor. In addition, investment costs were another often mentioned factor. They are too high for the majority of people to invest in household PV, without substantial financial aid from the government. Furthermore, the findings of the survey are pointing out that the costs for the energy production from hydro-power are too low for other RES, such as solar or wind energy, to compete with and that investments are very little. The majority of respondents also argue that in order to be competitive and attract investments, the energy market structure needs to change and adapt to the implementation of solar and wind power.

Furthermore, the survey includes the aspect of the regulatory instruments favoured by the experts. The law 1715 provides a political base for new mechanisms and regulations (see ??), e.g., the new regulations for auctions. The government announced in 2018 that auctions will be held for large-scale RES including solar PV, adopting the policy guidelines from law 1715.

One of the favoured instruments that interviewees mentioned, as shown in Fig. 5, was the promotion of solar Power Purchase Agreements (PPAs). Solar PPA contracts can be corporate or household PPAs, which both are bilateral agreements between an energy producer and consumer about a certain amount of electricity provided within an agreed time frame for a given price. The

[15] https://www.grupoenergiabogota.com/eeb/index.php/sala-de-prensa/comunicados-de-prensa/2018/, last access 01.02.2019.
[16] http://simulador.micodensa.com/, last access 23.03.2018.

Table 3
Overview over key data and assumptions for the quantitative analysis.

Data	Value	Source	Comment
Isolation	–	Pfenniger and Staffel [83]	loss: 10%, azimuth angle: 180°, tilt angle: 10°
Temperature	–	Berkley Earth Data Set	
Battery losses	8.8%		
Storage Prices	varies per size	[79]	
Solar Panel Price	0.748 €/W_p (Bogotá) 0.52 €/W_p (Barranquilla)	[84] (Bogotá) Expert assessment (Barranquilla)	exchange rates from the 06.08.2018
Labor costs	43 €/kW_p	Expert assessment	
Inverter Prices	varies per size	[79]	
Electricity prices in sectors 5 and 6	0.164 €/kWh (Bogotá) 0.178 €/kWh (Barranquilla) 0.5 €/kWh (La Guajira)	[85], Electricaribe[a] [65]	exchange rates from the 06.08.2018
Interest rate	4.25%	Central Bank of Colombia[b]	
Marketing fee	0.013 €/kWh (Bogotá) 0.018 €/kWh (Barranquilla)	[85]	exchange rates from the 06.08.2018
Stock exchange electricity price	0.033 €/kWh	Energía de Pereira[c]	exchange rates from the 06.08.2018

If La Guajira is not mentioned in particular in Table 3 the parameters of Bogotá were used.
[a] http://www.electricaribe.co/tu-energia/, last access 20.07.2018.
[b] https://tradingeconomics.com/colombia/interest-rate, last access 06.08.2018.
[c] http://www.eep.com.co/precio-de-energia-en-bolsa, last access 06.08.2018.

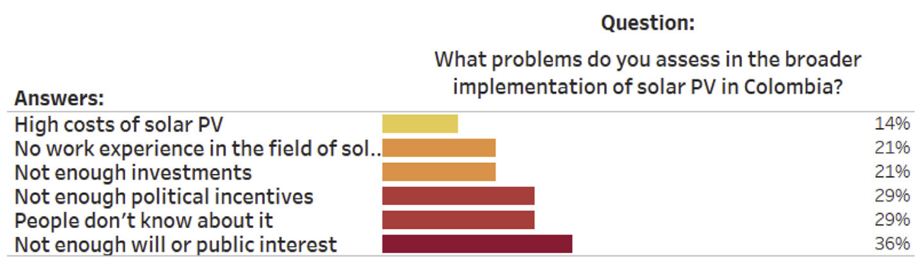


Fig. 4. Problems with the broader implementation of solar PV in Colombia.
Source: Own illustration

advantage of solar PPAs is that they take the burden of investment from the household owner, shifting it to a project developer. Meanwhile, such arrangement provides a reliable client for the project developer. The challenge for solar PPAs though are normally to find investors, which are willing to provide the upfront costs and see the long term benefits.[17] Furthermore, other regulatory measurements such as net-metering, tax reductions, FITs and microfinance were also mentioned and discussed by the respondents. Moreover, subsidies and cross-subsidies as well as feed-in tariffs are favoured by experts.

Looking at measures needed to make an energy transition possible, the results suggest various aspects to be considered. Firstly, the political will towards the transformation has to be strengthened. This can be achieved through an improved regulatory framework. In February 2018, after the survey was conducted, the resolution 030/2018 was passed introducing a way to sell energy surplus into the SIN through net metering. This marks a first step towards the needed political incentives suggested by the interviewees. Moreover, there is not enough awareness among the population that a transition of the energy sector is beneficial in the long run. The importance of a diverse range of RES is not recognized according to the evaluation of the survey. Therefore, another crucial factor is the enhancement of education and information about RES in Colombia that can be accomplished through public campaigns or public education in schools. The long-term benefits of investing into solar energy have to be pointed out, as well as the already existing incentives and possibilities. The highest potential for household implementation of solar energy is shown in the rural or countryside areas, where there is a low degree of electrification. In ZNIs the need for education and investment is one of the highest since people living there do not have the capital to invest nor the knowledge on how to establish RES systems [65].

Undoubtedly Colombia has a high potential for solar energy. As some respondent pointed out, this is specially true for La Guajira and Barranquilla. Therefore, the quantitative approach is applied to these specific regions, as well as to the capital city of Bogotá.

4.2. Prosumage model results

The lack of substantial financial aid and high prices, as mentioned above, lead to a rather unattractive investment situation. The implementation of net-metering and tax incentives, however, represent a major change in the regulatory framework [54]. The following paragraphs examine these insights from a quantitative perspective.

The simulation results of the current situation and possible future scenarios will be depicted in graphs only showing the positive IRRs to give a better overview of which combinations of PV and storage are profitable. The assumed PV step size is 0.5 kW_p and the storage step size is 2 kWh. The figures presented in Appendix A2 onwards show additional results for each case.

Fig. 6a shows the results using the consumer described in Table 2. The highest IRR for Barranquilla of 20.74% is reached at a PV size of 3.5 kW_p without storage capacity. Here, the consumption of the household and the production of the system matches best. To keep the initial cost of the PV system as low as possible, a small

[17] https://www.epa.gov/greenpower/solar-power-purchase-agreements, last accessed 09.11.2018.

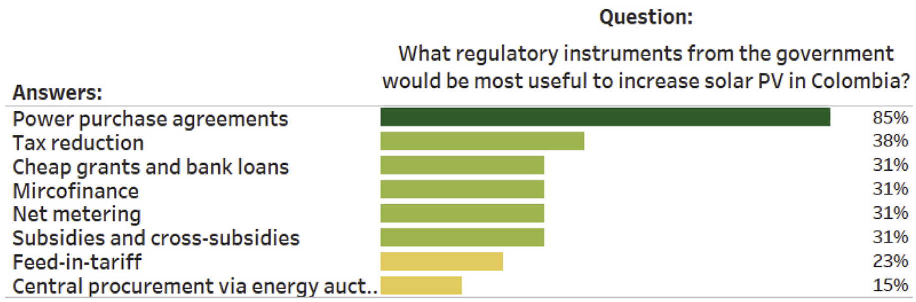
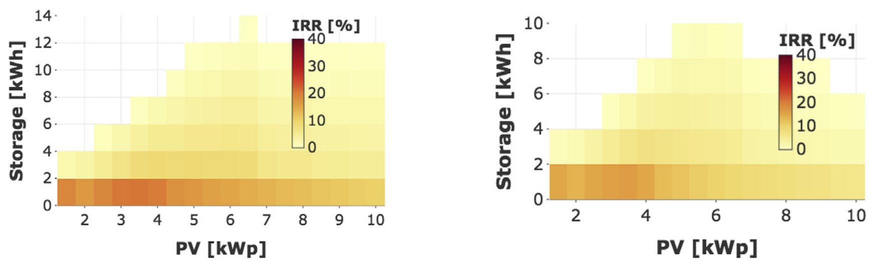


Fig. 5. Regulatory instruments to increase the share of solar PV.
Source: Own illustration



(a) Barranquilla (electricity price: 0.178 €/kWh).

(b) Bogotá (electricity price: 0.164 €/kWh).

Fig. 6. Internal Rate of Return (IRR) for Barranquilla and Bogotá with net-metering.
Source: Own illustration

share of the energy is drawn from the grid.

A bigger system including storage could cover almost the entire demand reaching autarky but the high investment would make this less profitable. It can be pointed out that PV systems without storage have the highest IRR which is mainly due to the high initial cost of storage. In the case of Bogotá, the results look very similar, as shown in Fig. 6b. The lower IRR (16.22%) is caused by the lower solar irradiation of Bogotá compared to Barranquilla and the additional transportation costs resulting in higher component prices.

With net-metering and without a FIT, the prosumager only saves money by covering his own consumption. High surpluses are only rewarded with the energy exchange price which is significantly lower than the single cost of electricity (see Table 3). Considering the tendency of falling storage prices due to technological innovations, economies of scale and increasing investment volume [86], sensitivity analysis were run to compare the expected IRR under several conditions. Considering an optimistic drop of storage prices up to 25% in the SIN the highest IRRs are still reached for stand-alone PV systems (Barranquilla 20.37% and Bogotá: 16.2%, both with 3.5 kW_p PV. This is a common side effect of net-metering since it makes it more profitable for prosumers to feed the electricity surplus into the grid instead of storing it [87]. Nevertheless, Fig. 7a shows that IRR of 11.26% can be achieved with a PV size of 3.5 kW_p and storage capacity of 2 kWh. In the case of Bogotá, the results are similar. The second highest IRR of 9.1% is reached at a PV size of 4 kW_p and storage capacity of 2 kWh.

Due to high electricity prices and the lack of net-metering, La Guajira is the region where systems including storage could be most attractive (see Fig. 8b) [15,31,53].

This region shows a high average of irradiation and therefore, a higher potential to increase prosumager savings and decrease the payback period. Since there are no opportunities to feed the self-generated electricity into the grid, net-metering was not considered.

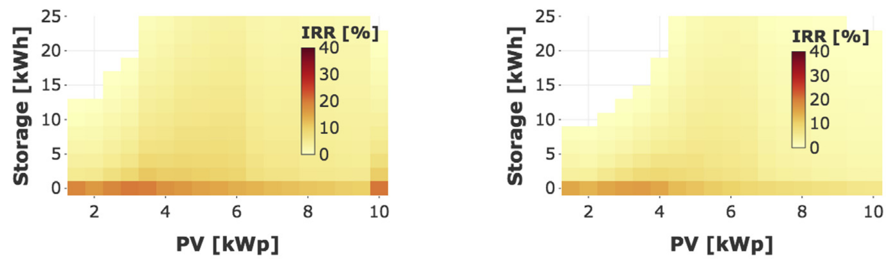
The current retail price is around 0.50 €/kWh [65] and three times higher compared to the other examined regions. Consequently, the IRR are a lot higher reaching 40.75% at a PV size of 1.5 kW_p without storage, as shown in Fig. 8a. Similar to the scenario above, the most profitable combinations do not include storage. Fig. 8b shows the case with 50% storage price. The most profitable configuration still includes no storage component but systems with medium sized storage (10–15 kWh) are becoming more profitable. This is due to the high initial investment cost for storage and the assumed distribution of demand. This observed pattern could change with the implementation of a technology specific support program to aliviate the initial investment of prosumage systems. Despite the high IRRs even stand-alone PV systems have not taken up in this region. This could change, if the government provides more information regarding RES and the advantages of prosumage systems to ensure public acceptance of these technologies and the policies implemented.

To simulate the current effects of the increasing inflation and potential effects of political instability due to changing governments, a further sensitivity analysis is conducted. In this case, the interest rate is increased up to 10% according to current tendencies of several banks in Colombia.[18] These results can be found in Appendix A2-A4.

5. Discussion of results

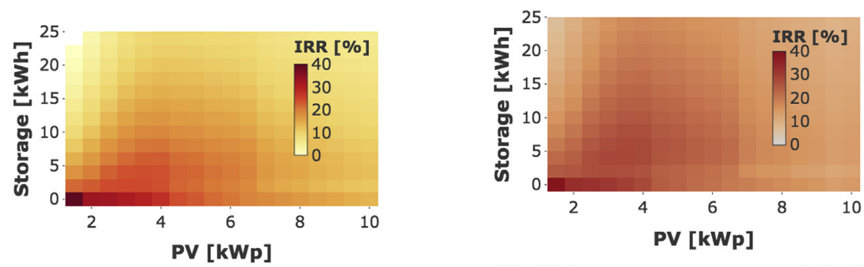
Regarding the qualitative part of this paper, the survey provided an overview of the experts' opinions. While, in-person interviews could have been carried out to have a more in-depth knowledge about the motivation behind the answers, most of the answers

[18] https://tradingeconomics.com/colombia/interest-rate, last access 23.01.2019.



(a) Barranquilla with 25 % storage price.
(b) Bogotá with 25 % storage price.

Fig. 7. IRR for Barranquilla and Bogotá with net-metering and 25% storage price.
Source: Own illustration



(a) Without net-metering.
(b) Without net-metering and 50 % storage price.

Fig. 8. IRR for La Guajira.
Source: Own illustration

seem to confirm some of the general insights that can be found in the literature or were mentioned during the exploratory interviews in the aftermath of the expert elicitation. According to the survey's respondents the main barriers to expand PV are financial preoccupations, insufficient tax incentives, expensive labor and technology costs, together with a resilient lack of clarity concerning the regulatory framework.

As for the quantitative approach, due to Colombia's high logistical costs [88], as well as the high costs for storage technologies, the simplifications might actually lead to higher installation costs in the case of Bogotá and La Guajira.

Furthermore, while there is no certainty that logistical costs will decrease in Colombia, cost estimations for storage technologies are much more encouraging. According to Ref. [89], the price for Lithium-ion batteries, the fastest growing storage technology, may decrease by as much as 61% by 2030.

It is important to highlight the fact that for the calculation of the energy surplus and the excess value, some parameters such as marketing fee and single cost of electricity, are changing constantly and depend on the retailer. For the energy exchange price, data for the past year (August 2017–July 2018) was collected and then averaged. According to Ref. [90] almost 40% of the single cost is attributed to electricity generation, around 36% goes to distribution, followed by almost 11% commercialization. The rest is incurred for transmission, losses and restrictions. Overall, the model uses an iterative approach to find the system optimums. Also, only one year (2014) is taken into account for calculating the economic profitability of solar PV and prosumage. Future analyses will have to look at multiple weather years.

Moreover, the model used could be expanded and adapted to other sectors by modifying the dataset for the specific demand of different types of households, such as those from sectors 1 to 4. Since stratification plays an important role in Colombia's power sector, further analysis on the impact of a prosumage system on the cross-subsidising scheme would be important. To do so, a further expert elicitation on the consequences and possible alternative to the stratification in cities could be helpful. According to Ref. [64] the distribution in sectors has been distorted throughout time and does not reflect the current living conditions of the households any more: Even though living conditions and wealth have increased, wealthier households in sectors 2 and 3 refuse to be upgraded due to the increase in public service tariffs this would entail. Consequently, these households may profit from the subsidies without justification, as mentioned in subsection 2.1; a clear disadvantage of such structure. Additionally [64], demonstrate that households with higher income can also be found in sector 1, as well as households with low income in sector 6. Overall, this represents a challenge for determining the potential of prosumage. In the model used, only households in sectors 5 and 6 are taken into consideration, assuming that these sectors can afford a PV system (first-movers) and could benefit from the electricity savings. Discussing the consequences for this was beyond our scope, but due to the distributional impacts of an eventual large-scale implementation of prosumage in sectors 5 and 6, it deserves a discussion on its own.

Given the current uncertainty in the future of cross subsidies for the different sectors, circumstances might change and prosumage could gain importance.[19] But the integration of RES can also have side effects on electricity prices, specially given Colombia's pricing scheme, because a major share of self-generated electricity and storage could not only increase the single cost of electricity, but also the redistribution of grid costs, as identified by Ref. [87]. A further analysis comparing similar systems, such as in Mexico and California, should be put into perspective. Overall, our approach and

[19] See for example news on a potential phase-out of these subsidies: https://www.elheraldo.co/barranquilla/el-estrato-3-se-queda-sin-subsidios-de-energia-y-gas-partir-de-2019-mauricio-gomez, last accessed 09.11.2018.

methods used are suitable to analyze the potential of solar energy in Colombia and the impact of the incentives newly implemented. The qualitative approach enables future changes in the political and regulatory framework to be taken into consideration while the quantitative approach can be used to examine the development and effectiveness of such changes by adapting the model used.

6. Conclusion

Since 1994, Colombia's regulatory framework concerning the integration of renewable energy has expanded. Initiating with the passage of laws 142 and 143 in 1994, additional, more ambitious laws and reforms have been developed ever since (e.g. 1715 renewable energy law of 2014). Together with the goals set in the Nationally Determined Contribution (NDC), this opens the path towards transforming the energy sector into a more sustainable one, as well as supporting a more diversified energy matrix. The latest resolution 030 by Colombia's Energy and Gas Regulatory Commission (CREG) issued in February 2018, implements net-metering as a regulatory tool; a feature highlighted by the experts consulted in the present study. Additionally, tax reductions have been put into place to further promote RES in Colombia.

The most favoured instrument detected by our survey, Power Purchase Agreements (PPAs), has not been proposed for household Photovoltaic (PV) yet. Additionally, according to the experts consulted, the tax incentives offered so far are not sufficient. The National Interconnected System (SIN) is still dominated by a few major players, making it difficult for smaller ones to enter the market under the current circumstances. Furthermore, the advantages of a diversified energy market have not been recognized by the public, making it difficult to increase the pressure on political stakeholders for further progress in the regulations.

On the other side, fading oil and natural gas resources along with more extreme natural phenomena, such as El Niño, demonstrate the need to diversify Colombia's energy mix. According to the simulation, especially in Non-interconnected Zoness (ZNIs) as La Guajira, PV can be one of the main drivers to achieve this. Systems without storage reached an Internal Rate of Return (IRR) of up to 35% assuming that the electricity price in these regions is around 0.50 €/kWh (i.e. off-grid systems). This correlates with the survey results that mainly regions without a working electricity grid can profit from decentralized PV and other unconventional RES. Especially La Guajira bears opportunities for smaller systems without and with smaller storage units, if storage prices continue to decrease. For Barranquilla and Bogotá, however, it was shown that prosumage is less profitable and IRRs are higher for systems without storage. Generally, the systems are less profitable and confirm the sentiments of the survey that private and small commercial PV systems will have difficulties to launch.

Colombia's unique energy market with its stratified sectors and strongly contrasting regions, makes it very difficult to anticipate effects of RES on the country as a whole. Private PV systems might lead to a higher inequality within the population since richer households could stop subsidising poorer ones when they produce their own electricity. On the other hand, such systems might represent a considerable opportunity for households with excessively high electricity costs or without connection to the grid. Looking forward, a society-wide debate on the sustainability of the existing cross-subsidy-scheme is needed.

Furthermore, looking at the global energy transition, moving away from fossil fuels, especially coal, is necessary to tackle climate change. The resulting trends - divestment and decreasing coal demand, especially in Europe where several countries have already decided on a coal phase-out - represent a major risk for Colombia; the world's fourth largest coal exporter. While the low production costs and high quality of Colombia's coal might seem to be an advantage, it can turn out to be a dangerous mirage due a potential devaluation of fossil fuel investments and resulting stranded assets. This would have severe consequences on Colombia's mining industry, exports and job market, as depicted in the study by Ref. [5].

In conclusion, the survey underlines an array of different possibilities to accelerate the energy transition in Colombia. With the newly elected government in 2018 and incoming new regulations, the topic will gain importance and open new possibilities for investors and other market players in the industry. The prosumage model used examines the effectiveness of the current regulatory framework for households and prospects the future development of PV systems combined with storage. There are steps to be taken to promote more PV in Colombia beside the laws and measures already in place. The development of recent years, economic growth, new legislation, and a more stable political situation in the aftermath of the peace process, all open the path to transform the energy sector towards more sustainability, reliability and more independence from fossil fuels. It remains to be seen, whether the political will to realize this potential will ensue.

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Appendix

A1. The public institutions of the electricity market

Colombia's electricity market is divided in electricity generation, transmission, distribution, and retail. Even after the liberalization of the energy market in 1994, distribution and transmission remained largely state-owned [65]. Therefore, from a regulatory perspective, the following public institutions play a key role.

- *Ministry of Mines and Energy (MME)*: primarily in charge of defining new energy policies or proposing law modifications and updates.
- *Energy-Mining Planning Unit (UPME)*: establishes energy requirements and constraints which are part of the National Energy Plan and Expansion Plan for the energy sector.
- *Colombia's Energy and Gas Regulatory Commission (CREG)*: as the sector's regulator, it works with other institutions to oversee all operations and transactions regarding electricity generation and transmission.[20]

A2. Additional result graphs for Bogotá

[20] http://www.creg.gov.co/cxc/secciones/mercado_mayorista/estructura.htm, last access 23.03.2018.

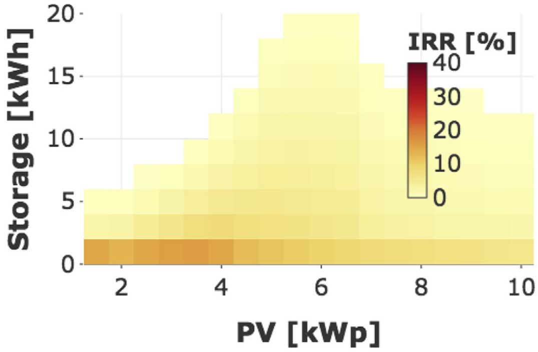


Fig. A1. IRR for Bogotá with 50% storage price.
Source: Own illustration.

A3. Additional result graphs for La Guajira

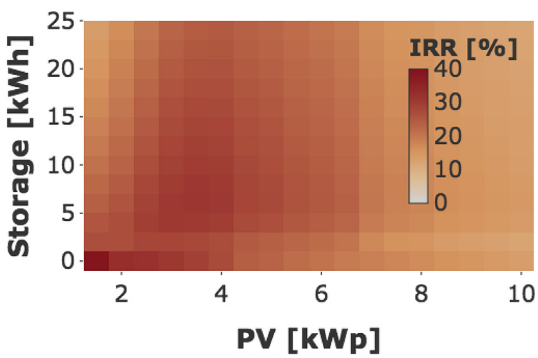


Fig. A2. IRR for La Guajira with 25% storage price.
Source: Own illustration.

A4. Additional result graphs for Barranquilla

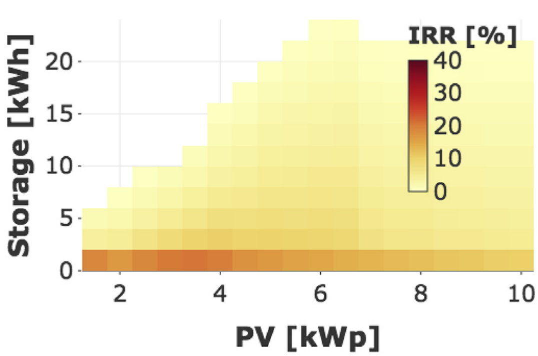
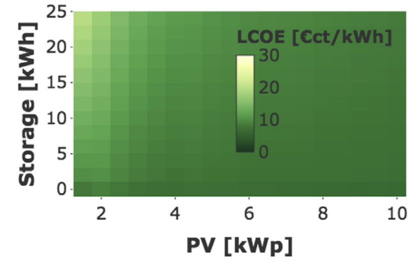
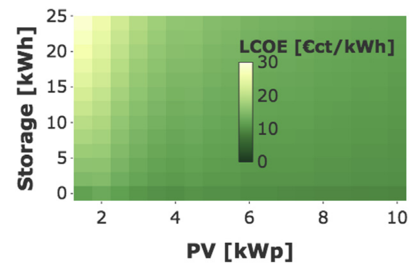


Fig. A3. IRR for Barranquilla with 50% storage price.
Source: Own illustration.



(a) Barranquilla with regular interest rate of 4,25 %.



(b) Barranquilla with 10 % interest rate.

Fig. A4. LCOE for Barranquilla.
Source: Own illustration.

In Figure A4a the LCOE in €ct/kWh is shown for Barranquilla. Again the best results are without storage but this time at the maximum of 10 kW_p. Here the minimum of 6.28 €ct/kWh is reached. A worsening of Colombia's financial situation and an increasing interest rate would lead to a distinct rise of the LCOE. Figure A4b shows this effect clearly. Here the minimum at no storage and 10 kW_p rises up to 9.24 €ct/kWh.

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