PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING
THE UNIVERSITY OF EDINBURGH
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INCREASING THE PENETRATION OF RENEWABLE ENERGY THROUGH COMMUNITY ENERGY PROJECTS. AN ECONOMIC APPROACH BASED ON BIFORM GAMES

FABIÁN ANDRÉS FUENTES GONZÁLEZ

Thesis submitted to Pontificia Universidad Católica de Chile and The University of Edinburgh in partial fulfilment of the requirements for the Degree of Doctor in Engineering Sciences and Ph.D. in Engineering.

Advisors:

ENZO SAUMA & HARRY VAN DER WEIJDE

Santiago, Chile, November, 2019

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To my mother.

"I can do all things through Christ who strengthens me" (Philippians 4:13)

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LIST OF MAIN ACRONYMS (SHOWN BY ORDER OF APPEARANCE)

GW	Gigawatts
Ppm	Parts per million
°C	Celsius degrees
MW	Megawatts
CO2	Carbon dioxide
GtCO2	Gigatonnes of carbon dioxide
AC	Alternating current
DC	Direct current
kW	Kilowatts
GWh	Gigawatts-hour
MWe	Electric megawatts
MWth	Thermal megawatts
CSP	Concentrated solar power
GWe	Electric gigawatts
kWp	Kilowatts peak
USD	U.S. dollar
CHF	Swiss franc
EUR	Euro
GBP	British pound sterling
CLP	Chilean peso
p	Pence
kgCO2	Kilograms of carbon dioxide
km	Kilometres
kV	Kilovolts
p.u.	Per-unit

ABSTRACT

In 2014, the Chilean government promulgated the Law 20,571. This law gives to regulated clients, mainly residential electricity customers, the right to produce energy/electricity for self-consumption and sell any surplus to the grid. After five years of implementation, including an update in 2018, the installed capacity of these projects is still very low. In contrast, in Scotland it is possible to find a much higher citizen participation in energy production through more collective initiatives, specifically community energy projects. This situation begs important questions about the effectiveness of net billing schemes in promoting citizen participation in energy production. In this doctoral thesis, a variety of tools inspired by game theory, social science, and mathematical programming are used and adapted to answer these questions. This leads to the following findings. Firstly, the current Chilean net billing scheme may not be the best support mechanism for citizen-led energy production developments. Secondly, some residential electricity customers would be willing to participate in local energy initiatives by devoting money and/or time, even when their main concern is the lack of financial resources necessary to fund such projects, and project ownership can influence this willingness. Thirdly, community energy projects can be the best strategy to follow for residential electricity customers in Scotland and Chile, although cost subsidisation can further improve community energy incentives. Even when the incumbents do not know their share of the benefits at the time of choosing a particular energy production scheme or mechanism, community energy projects present more opportunities to be implemented in comparison with net billing schemes in both countries. Finally, under specific circumstances, community energy deployment can have positive effects on variables like social welfare, consumer surplus, nodal prices, and carbon dioxide emissions. Based on these findings, we then draw conclusions and recommendations, which can help further development in the community energy sector, particularly in Chile.

RESUMEN

En el año 2014, el gobierno chileno promulgó la Ley 20.571. Esta ley da a los clientes regulados de electricidad, mayoritariamente clientes residenciales, el derecho de producir energía/electricidad para autoconsumo y de vender cualquier excedente disponible a la red. Después de cinco años de implementación, incluyendo una actualización a dicha ley en el año 2018, la mayoría de los proyectos representan una baja capacidad instalada. Por el contrario, en Escocia es posible encontrar una capacidad instalada mucho más alta asociada a participación ciudadana en generación de energía, a través de iniciativas más colectivas, particularmente proyectos comunitarios de energía. Esta situación motiva el establecer algunas preguntas sobre la efectividad de los esquemas net billing para promover la participación ciudadana en generación de energía. A través de esta tesis doctoral, usamos y adaptamos una serie de herramientas inspiradas en los campos de la teoría de juegos, ciencias sociales y programación matemática. Después de usar tales herramientas y, por lo tanto, responder las preguntas anteriormente mencionadas, podemos destacar los siguientes hallazgos: primero, el actual esquema chileno de net billing no sería el mejor para apoyar desarrollos de producción de energía ciudadanos; segundo, algunos consumidores residenciales de electricidad tendrían la voluntad de participar en iniciativas locales de producción de energía vía donando dinero y/o tiempo, aun cuando su mayor preocupación es el financiamiento de dichos proyectos, y la propiedad de los proyectos influiría en tal voluntad; tercero, los proyectos comunitarios de energía pueden ser la mejor estrategia a seguir por los consumidores residenciales de electricidad en Escocia y Chile, los costos subsidiados pueden mejorar los incentivos para el despliegue de dichos proyectos, y aun cuando los incumbentes no saben cuan bien podrían estar al momento de elegir un esquema de producción de energía u otro, los proyectos comunitarios de energía presentan mayores oportunidades para ser implementados en comparación con proyectos net billing en ambos países; finalmente, habrían efectos positivos en variables como beneficio social, excedente del consumidor, precios nodales y emisiones de dióxido de carbono, derivado del despliegue de proyectos

comunitarios de energía bajo circunstancias específicas. En consecuencia, establecemos conclusiones y recomendaciones que pueden ayudar a un desarrollo más profundo de los proyectos comunitarios de energía, particularmente en Chile.

INTRODUCTION

Climate change is probably the most worrying threat mankind has faced in recent times. It is worrying because it involves not only climatic or meteorological aspects but also derived implications with unsuspected consequences. These consequences are strongly linked to social, economic, and environmental matters that model, define, and guide the daily life of people around the world. In the late eighties, a pioneering call for action was made by the Brundtland Commission (World Commission on Environment and Development - WCED) to make significant efforts to assure economic growth, environmental protection, and social equality [1]. After twenty years or so from that call, things seem to have improved in several aspects, but there are still many challenges ahead, particularly, in terms of guaranteeing economic growth, environmental protection, and social equality; in other words, an efficient and equitable sustainable development.

Regarding the above, the worldwide electricity and heat sector plays a key role in the three above-mentioned pillars of sustainable development, as it is one of the fundamental drivers of economic growth and social equality. It provides access to basic services for industries (and people), which allow and facilitate the provision of other more complex services and goods that improve people’s quality of life every single day such as, health, safety and security, food, leisure, and so on. At the same time, these contributions to economic growth and social equality often come at a cost to the environment. In 2016, the sector accounted for 42% of the total global carbon dioxide (CO_2) emissions in the world [2]. These CO_2 emissions are very important considering the current CO_2 concentration in the atmosphere, which has already exceeded the 400 ppm, magnitude that is over the highest historical CO_2 level of 300 ppm (as quantified by data reconstruction from ice cores) [3]. As generally known, CO_2 traps the heat that is released through human activities (anthropogenic emissions), which implies a variety of negative consequences to the biosphere, including permafrost melting and the corresponding retained methane release, slower forestation, decreasing solar radiation reflection and the corresponding rise of sea water levels and temperatures, thermohaline currents weakening and the corresponding changes on the natural continental temperature regulation, among others. Although the installed capacity of renewable energy has grown from approximately 995 GW in 2007 to more than 2,179 GW in 2017 [4], we still need to enact effective measures to reduce pollutant emissions, as fossil fuels currently constitute about two thirds of the global power installed capacity [5].

All the aforementioned consequences derived from CO_2 emissions and the resulting climate change would imply a variety of impacts that may damage economic growth as well as social equality, recalling the sustainable development concept. Several estimations highlight that impacts in developed countries might imply, for example, welfare loss (especially in poorer countries) [6], damage to critical crops for world food security, such as corn and soybeans crops in the United States [7], severe loss in the economic value of European forest land [8], specific impacts on agriculture, river floods, coastal areas, tourism, and human health with potential significant reductions in household welfare and annual welfare growth in the European Union [9], a reshaping of the global economy with a drop on the average global income and a rise in global income inequality derived from unmitigated warming [10], negative impacts on gross domestic product per +1°C on average and a larger economic inequality in the United States [11], significant land losses in Europe derived from a sea-level rise [12], water availability stress and river flooding [13], among others. Of course, developing counties like Chile are no exception and also face challenges related to climate change. According to the Climate Change National Action Plan 2017-2022 established by the Chilean government, Chile is highly vulnerable to climate change due to the existence of a low lying coastal area, arid and semiarid zones, forests, land exposed to natural catastrophes, areas that are prone to drought and desertification, urban zones with atmospheric pollution, and mountainous ecosystems. This implies many consequences such as a rise on temperatures across the country [14], changes to precipitation patterns with a significant drop on rainfall [15-17], an increase in the frequency of extreme climatic events [18], biodiversity damage, water availability stress and drought, illnesses proliferation, impacts on public infrastructure, lower installed capacity based on hydro energy, agricultural land displacement across the country [14], harmful effects on fisheries [19-22], pressures on the tourism sector and public services [14], etc.

Based on the evidence shown above, climate change would clearly impact most of the countries around the world, including Chile, in different areas, which would mean a significant damage to economic, social, and environmental aspects of human life. It is therefore clear that CO_2 emissions reduction is imperative and mandatory, so the best options to achieve this need to be properly explored and evaluated by policy-makers and implemented by governments, ideally in the short-term. However, even though some basic solutions to this problem have been relatively well-known for years (for instance, limit fossil fuels consumption, upgrade public and private infrastructure, reduce commuters and travellers' journeys, decrease goods and services consumption, be more efficient in terms of the use of energy, eat vegetarian food, avoid deforestation, constrain birth rates, replace fuels, among others [23]), the reality is more complex, so the effectiveness of dealing with this global issue might not be as high as expected years ago, especially considering the consumer-side of the problem and its solutions. The key numbers on CO_2 concentrations (400 ppm) and annual emissions (from 33.42 $GtCO_2$ in 2010 to 36.18 $GtCO_2$ in 2016) [24,25] only confirm this statement, even though the renewable energy participation in the world generation mix more than doubled in ten years, as noted above.

In this context, some authors have argued that the current growth rate of renewable energy installed capacity is not enough to tackle climate change even when wind and solar costs have dropped significantly [26]. Other authors have recently said that even a scenario with 100% renewable energy would not be sufficient [27]. Moreover, some estimations highlight that coal-fired power plants could keep their relevance in the world generation mix until 2040, due to the useful life of such plants in Asia where they are 11 years old on average, indicating several operational decades ahead [28]. Hence, an effective, sufficient, and timely transition towards a carbon-free electricity and heat sector could be at risk. These facts (and many others) illustrate that the challenge that is being faced is huge and therefore the relevance of transforming the power sector into a zero-carbon industry, as soon as we possibly can, cannot be denied. Currently, this energy transition is dependent on (quite few) large companies or generators. For example, in the United Kingdom (UK) the electricity generation sector is led by a small number of large power companies, which represent almost 50% of the wholesale electricity market[1] [29]. In Chile, a similar situation can be observed as the electricity market is led by five large generation firms[2], if a total installed capacity greater than 1,000 MW [30] is considered. Thus, it seems that new ways of thinking and conceiving the energy and electricity markets need to be taken into account, apart from widely-known specific activities based on the customer-side or producer-side of the solution, namely, reduce fossil fuels consumption, shorten commuters and travellers' journeys, limit goods and services consumption, etc.

Other ways of thinking and conceiving the energy and electricity markets have started to be explored in the literature. In particular, a new way of making the demand-side involved in energy production, not as a mere spectator or influencer but as true participant and decision-maker, is being considered. Ackermann et al. [31] propose one of the most relevant definitions in this sense: the concept of distributed generation. This concept can be simply defined as "an electric power source connected directly to the distribution network or on the customer site of the meter". Of course, the precise definition may vary in each country around the world given the specific legal, regulatory, technical, and economic context. This concept has recently attracted a lot of attention, even though a more decentralised way of producing energy is not an entirely new paradigm, as in the beginning of the electricity markets the first power plants only supplied customers near their location, due to an DC-based transmission system, which implied a constrained voltage and a shorter delivery distance [32]. There are some drivers that play a key role in

[1] EDF (29.1 GW), RWE (14.0 GW), and SSE (9.7 GW).
[2] ENDESA (ENEL) (3.8 GW), Colbún (3.3 GW), AES Gener (2.4 GW), ENGIE (1.6 GW), and CELTA (1.0 GW).

the emergence of more decentralised energy systems, such as technological developments, more limitations to the construction of long transmission lines, a larger demand for reliable energy services, liberalised electricity markets, climate change and other environmental concerns [33]. Pepermans et al. [32] notice that two drivers chiefly contribute to an increasing interest in distributed generation: liberalised electricity markets and environmental concerns. Alanne & Saari [34] highlight that such distributed generation systems may contribute to an effective peak load management, capacity reliability and quality, local network use and expansion, combined heat and power deployment, more affordable energy sources, among others. The same authors also note that these elements would justify a deeper connection or alignment to the concept of sustainable development. However, there are disadvantages and challenges to face as well, including significant implementation costs, misaligned market incumbents' incentives, unbalanced energy supply and demand, impacts on grid frequency and voltage, and other technical issues mainly due to power flow variations, AC-DC interfaces, and a lack of synchronous generation [32].

It should be noted that the concept of distributed generation, as it was conceived and defined, seems to imply a more individualistic concept of decentralised energy production and does not explicitly take into account social aspects, which are very important at the time of developing and implementing any project that may impact people's life and the environment. Social aspects imply a diversity of factors, for example, how harmful or beneficial an energy production project could be, what specific benefits such a project will provide to people, how project costs and risks are accounted and managed by project developers, how people can participate in the decision-making processes, etc.

Here, another concept emerges as an option, which explicitly considers social aspects in energy production: community energy. Walker and Devine-Wright [35] identify two underlying dimensions of this concept: process and outcome. The former relates to who develops and runs the project, and who is involved and has influence. The latter relates to how the outcome is spatially and socially distributed. They also establish that an ideal community energy project would be a renewable energy project that is entirely driven and carried out by a group of people and also benefits the local community. This is because such project becomes less controversial and divisive among the community members, as there is a direct and more profound involvement and the benefits are shared among people [35]. Given that the term community energy explicitly involves a more social perspective about energy generation, there are more concepts related to the social sciences that explain and play a key role in the emergence of such projects, including interpersonal and social trust [36], structural and symbolic resources [37], community ownership [38], among others. Of course, the relevance of more technical concerns related to the area of electric power studies cannot be denied and deserves to be taken into account, but that is beyond the scope of this thesis. Despite the complexity of such terms, it is possible to find many community energy projects that are currently generating energy and benefitting people in a more sustainable way, particularly in European countries like Germany, Denmark, Spain, England, Scotland, Wales, the Netherlands, Sweden, Italy, etc. As in a distributed generation paradigm, community energy can also take many specific legal forms and/or organisations depending upon their specific legal, regulatory, technical, and economic context, but the essence or nature of a community energy project does not vary: an energy production project made by and for people.

Both aforementioned terms come under the umbrella of a wider notion: citizen participation in energy production. As a consequence, policy-makers, local authorities, and governments, should decide in which way citizen participation in energy production should be promoted and deployed in a particular place, which can be incentivised through net billing schemes, net metering schemes, community energy projects, locally-owned energy initiatives, and many other concepts or definitions that can be found in the specialised literature today.

Chile decided not to be left behind, and its government in 2014 promulgated the Law 20,571, commonly called "distributed generation or net billing law" [39]. This law gives to regulated clients the right to produce energy/electricity for self-consumption and sell any surplus to the grid. In the same vein, the Chilean government also launched Chile's Energy Policy 2050, in which it explicitly sets out some goals related to the associativity between communities and private organisations/companies for promoting local developments, deployment of community-led or joint-led energy projects, distributed generation and electricity demand management mechanisms [40]. However, although this law was promulgated and the government explicitly established a positive attitude to citizen participation in energy production initiatives, the Chilean net billing scheme as defined in Law 20,571 did not seem to yield as much result as expected. Some incumbents in the electricity market claimed that the law was not entirely aligned with customers' needs and companies' incentives, citing economic, technical, and legal reasons[3] [4]. In fact, at the end of 2016, there was less than 2 MW of installed capacity derived from net billing scheme projects in Chile. Considering this situation, the government began negotiations to modify the net billing law. This update came in 2018, with modifications to the maximum generation, the possibility of implementing joint ownership projects, payments for energy injections made by residential customers with up to 20 kW of installed capacity (when their electricity consumption expenses are exceeded), among others[5] [6] [41]. Yet, although the total installed capacity derived from net billing projects increased remarkably during the last few years, the projects (in terms of quantity) still represent a low installed capacity. This implies that most of the net billing capacity is not justified by a real inclusion of residential electricity customers in energy production. In this sense, the Chilean government recently stated that the net billing law is to promote self-consumption [41], which would contradict what has been written in Chile's Energy Policy 2050.

[3] See https://www.nuevamineria.com/revista/generacion-distribuida-una-ley-en-deuda/
[4] See http://www.revistaei.cl/entrevistas/cara-a-cara-se-debe-reformular-la-ley-de-generacion-distribuida/#
[5] See http://www.revistaei.cl/2018/08/03/estos-los-principales-cambios-del-proyecto-ley-modifica-la-generacion-distribuida/
[6] See http://www.revistaei.cl/reportajes/la-apuesta-la-generacion-distribuida/

In contrast, in the UK, citizen participation in energy production began to be promoted much earlier, through official statements as a way to strengthen communities and the energy/electricity market in a more sustainable way [42,43]. This boost supported the creation of several public, private, and third-sector organisations with the objective of encouraging and helping communities that wanted to participate in energy production. At the same time, the British and devolved governments started to create financial and technical aid schemes that provided (and still provide) key support to facilitate the deployment and implementation of the concept of citizen participation in energy production. Within the UK, one of the most remarkable examples is Scotland, where the community and locally-owned energy sector began with an installed capacity of 1.2 MW in 2011, based mostly on wind energy technologies and helped by the British feed in tariff scheme [44], to migrate towards an installed capacity of 697 MW in 2018, which is not only based on wind energy but also on other renewable energy sources [45]. Behind this apparent success was an ambitious goal set by the Scottish government in 2011, which established a target of 500 MW of installed capacity based on community and locally-owned energy by 2020 [46-48]. However, given the current situation the Scottish government now set a new target of 1 GW by 2020 [45]. Concerning the above, the community-owned energy sector alone currently represents nearly 80 MW of installed capacity, a magnitude that demonstrates a remarkable evolution especially during the last 6 years. This is very important, not only because of the installed capacity, but also because of the potential benefits that communities can derive from such projects. Those benefits may consist of direct profits that can be used for improving local economy (via employment, for example) or carrying out other social activities (local refurbishments, for instance). This is a huge difference in comparison with schemes like net billing, where the benefits are primarily allocated to just one individual, which might even be a private company and not a residential electricity customer.

Making simple comparisons between both countries, it seems that the Scottish experience in citizen participation in energy production deployment, principally through the emergence of a community energy sector, may provide useful lessons to other countries, especially emerging ones like Chile, that want to develop and deploy their own. The contrasts between Chile and Scotland could indicate that a deeper involvement of communities in energy production might imply a higher citizen participation and then a more successful outcome; in terms of new citizen-based renewable energy installed capacity, at least. Alternatively, more collective energy production schemes (community energy) might imply better results than more individual energy generation schemes (net billing). Of course, this begs several more specific questions: Is the Chilean net billing scheme appropriate to foster citizen participation in energy production? Do people (alternatively: residential electricity customers) really want to participate in energy production? What social factors influence citizen participation in energy production? Is community energy more attractive than net billing schemes to promote citizen participation in energy production? What impacts could the deployment of community energy projects have on electricity markets? The answers to these questions could, of course, relate to complex factors such as historical, sociological, psychological, and cultural factors that are beyond the scope of this work. Nevertheless, there are some more practical tools that can help to better understand this phenomenon.

The methodology followed in this work, in order to answer the aforementioned questions, considers the use of game-theoretical tools (i.e. biform games and linear production games), which can help to deal with questions related to the economic-strategic viability or convenience of a particular initiative. Moreover, some social science techniques like Likert scale-based surveys and regression analysis are also considered in this doctoral thesis, which can help find clues about people's feelings, desires, or preferences about a particular initiative. Furthermore, mathematical programming or optimisation modelling is also taken into account in this work, which addresses questions about the impacts of community energy initiatives on key economic variables such as prices, production quantities, profits or social welfare, etc.

Hence, this research takes the Scottish and Chilean experiences in citizen participation in energy production into account, and develops simple and pioneering cases and examples focused on solar PV technologies, in order to answer the aforementioned questions. To do so, we consider real-world data chiefly taken from Chilean and Scottish/British sources and use all the above-mentioned tools, in order to contribute to the state-of-art by providing valuable evidence that might help policy-makers, governments, and other stakeholders to design and implement proper public policies that increase the penetration of renewable energy through citizen participation. This may contribute to CO_2 emissions reductions, provide customers a real and effective involvement in the energy/electricity markets, democratise and strengthen such markets, increase the customers' wealth and social welfare, have positive effects on retail prices, and so on. In this sense, this work addresses and examines these elements, which implies the following main results/findings:

Firstly, the net billing scheme currently in force in Chile may not be the best support mechanism for citizen-led energy generation initiatives. Secondly, some residential electricity consumers would be willing to participate, by investing money and/or devoting time, in local energy initiatives, even when the lack of financial resources necessary to fund such initiatives is their main worry, and project ownership can influence this willingness. Thirdly, community energy projects can be the best strategy for residential electricity consumers in Scotland and Chile, although cost subsidisation can further improve the incentives for community energy developments. Community energy projects show more opportunities to be implemented in both countries, even when the incumbents do not know their share of benefits at the time of choosing a particular energy generation scheme. Finally, under particular circumstances, community energy initiatives can have positives effects on social welfare, consumer surplus, nodal prices, and carbon dioxide emissions.

Based on these findings, we draw conclusions and recommendations shown later in this doctoral thesis, which can help further development in the community energy sector, particularly in Chile.

Research hypotheses

This research mainly addresses two hypotheses, which can be presented as follows:

1. The current Chilean net billing scheme is not the most effective scheme to promote and deploy citizen participation in energy production in Chile, especially with regard to community energy projects.
2. The implementation and deployment of community energy projects in Chile may lead, at least under certain circumstances, to positive economic and environmental impacts on the whole power system.

General and specific objectives

The general objective of this thesis is verifying the aforementioned hypotheses and providing a more effective market mechanism or scheme to promote and deploy citizen participation in energy production in Chile.

The specific objectives are shown as follows:

1. Survey the current literature about the Scottish experience in community energy emergence, and analyse the Chilean current situation to determine the key differences between these two countries.
2. Investigate the appropriateness of the current Chilean net billing scheme, one of these key differences, using game theoretical tools.

3. Examine residential electricity customers' willingness to participate in energy production and especially the relationship between customers' sense of ownership of energy projects and their willingness to devote time and money to these projects, by using social science tools like Likert scale-based surveys and regression analysis.
4. Determine the economic-strategic incentives for implementing and deploying community energy projects by using novel hybrid game theoretical tools.
5. Examine the potential effects of community energy developments on electricity markets using advanced optimisation models.
6. Contribute to the state-of-art literature and derive useful lessons and recommendations to help policy-makers, governments, and other stakeholders to design and implement proper public policies that increase the penetration of renewable energy through citizen participation, particularly community energy projects.

Main contributions of the thesis

The main contributions of this doctoral thesis can be summarised as follows:

1. This thesis gathers evidence from different sources and disciplines, about the Scottish community energy sector development, which will be useful to many readers.
2. This is a first systematic attempt to characterise the Chilean community energy sector and compare it with similar sectors elsewhere.
3. This is the first attempt to analytically demonstrate the inconvenience of the current Chilean net billing scheme for residential electricity consumers, by using non-cooperative game theory.
4. This is the first systematic effort that explores and determines whether Chilean residential electricity customers are willing to participate in energy production initiatives, and what the key drivers of their willingness to devote time or money are.

5. This is a first attempt at explicitly including ownership matters in quantitative studies about citizen participation in energy production, and the first study to show that these ownership matters are a key explanatory variable of citizen participation.
6. This is the first attempt to characterise the Scottish and Chilean community energy sectors by using novel hybrid games theoretical tools, particularly biform games.
7. This is the first effort that formally characterises and includes community energy projects in generation and transmission expansion optimisation problems, by using biform games and linear production games.
8. This is the first attempt to demonstrate the usefulness of using biform games to analyse increasingly complex electricity markets.
9. This is the first work explicitly focused on community energy development in Chile, which presents valuable evidence and useful lessons and policy recommendations.

Structure of the thesis

The main body of this doctoral thesis has been organised in four chapters (plus the final remarks and general conclusions presented afterwards, at the end of this thesis), in which we attempt to address the aforementioned research hypotheses by answering the above-mentioned questions. Accordingly, the corresponding structure of this thesis is shown as follows:

In chapter I, we present an overview of the relevant evidence available regarding the Scottish experience in relation to the development of community energy projects. We also characterise the Chilean context and further analyse the current Chilean net billing scheme using concepts from non-cooperative game theory. We then derive lessons from the Scottish experience and define a list of policy recommendations for Chile, which can help further development in community energy. The text in this chapter is based on a manuscript that has been accepted for publication in Renewable and Sustainable Energy Reviews.

Chapter II presents an exploratory quantitative assessment of the preferences for local energy initiatives based on solar photovoltaics technologies, carried out through an online survey focused on residential electricity customers who live in Region Metropolitana, Chile. We explicitly include the concept of ‘sense of ownership’, for which we also propose a specific definition. We use the corresponding results to draw conclusions for strengthening citizen participation in energy production.

Chapter III presents simple and novel three-player bi-form coalitional games, which analyse community energy projects in Chile and Scotland taking into account two methods based on biform games theory. These games are based on real-world data about community energy projects, net billing distributed generation schemes and ordinary utility contracts. We use these games to derive insights about the economic-strategic viability of community energy projects and draw conclusions for the community energy sector, simultaneously showing that biform games can be a valuable tool to analyse increasingly complex electricity markets. The text in this chapter is based on a manuscript that has been submitted for publication in Energy Economics.

Finally, in chapter IV, we present a bi-level generation and transmission planning optimisation model, which combines biform games and linear production games, to analyse the impact of the community energy sector emergence on wider electricity markets. The model is formulated as a mathematical program with equilibrium constraints (MPEC) for which the corresponding Karush–Kuhn–Tucker (KKT) conditions are obtained, in order to integrate all the incumbents’ problems considered in the model. When solving this problem we examine the effects on social welfare, consumer surplus, nodal prices, demand and generation of electricity, transmission expansion, and CO_2 emissions. We then draw conclusions for the community energy sector and show that biform games and linear production games can be valuable tools to work on energy markets complexities through optimisation models. The text in this chapter is basically based on a manuscript that has been submitted for publication in Applied Energy.

I. THE SCOTTISH EXPERIENCE IN COMMUNITY ENERGY DEVELOPMENT: A STARTING POINT FOR CHILE

I.1 Introduction

In recent years, the idea of local and/or civic participation in energy generation has been part of renewable energy targets defined by governments in the UK and Europe, in order to implement energy production projects in a sustainable and decentralised way.

In 2003 and 2005, the UK Government released two reports, which contained statements about encouraging actions performed by citizens aimed at implementing local/community renewable energy projects [42,43]. Those statements were not mere rhetoric. In fact, many organisations were, at that time, already operating in the community energy sector, including the Scottish Community and Households Renewables Initiative, and the Energy Saving Trust (EST), which provide advice, training and funding, among other services [36]. Since then, additional initiatives have been launched by the UK and devolved governments around the UK [49], such as the Welsh Assembly's Community Scale Renewable Energy Programme, the Community Renewable Energy Fund, etc. Generic support schemes for renewable energy have helped community energy developments as well. Apart from the Renewable Obligation System implemented in the UK, a Feed-In-Tariff (FIT) scheme has been implemented since 2010 [50]. There are also other initiatives such as the Seed Enterprise Investment Scheme (SEIS), which offers a tax relief that could apply to some renewable energy projects [51-53]. These schemes help to increase the amount of renewable energy generating capacity, as well as support the deployment of citizen participation in energy generation projects.

Despite this, some critical views have also been voiced. Some authors argue that current support schemes are useful but not sufficient, and that they need to be complemented with other policies. They also criticise the UK’s position as ambiguous, because community energy is being promoted without significant changes in the large-scale generation mix, as a small number of companies dominate the British energy sector, and isolated policies, like the FIT scheme, are unlikely to change the prevailing policy framework, which is based on large-scale developments [52,54]. Bomberg & McEwen [37] show that uncertainties related to support schemes could inhibit the progress of community energy projects. Frantzeskaki et al. [55] argue that, despite a political desire for community energy, existing mechanisms and policies are inconsistent and incompliant. Underlining this perspective, Berka et al. [56] show that community energy projects face higher costs due to several factors, such as internal processes, diseconomies of scale, local opposition and acceptance, among others. Moreover, despite the existence of around 5,000 community energy groups up to March 2015 in the UK[7] [57,58], the electricity generation is led by few "major power producers" [59]. Thus, in the UK, the trend would imply a redistribution of just a small part of the whole generation mix towards communities, while other economic agents, such as some householders, farmers, and public bodies, would benefit more from this shift [60]. Nevertheless, the role of communities in energy production is recognised in the UK (and especially in Scotland) through the aforementioned elements by the incumbents of the British energy market. Even the small share of community energy projects in the UK's generation mix is significantly larger than other countries, especially in Scotland.

There may therefore be useful lessons to be learned from the UK, and particularly, the Scottish approach to community energy, which could help countries that want to develop their own community energy sector. This chapter focuses on Chile, which has an incipient but still weak community energy sector, despite some interest in further development from the government. In this chapter, we provide an analysis of the Scottish community energy sector and its development, compare this with other European countries and the current situation in Chile, and draw out conclusions for Chilean policy.

[7] More recent studies indicate around 3,500 groups involved in community energy [58].

The rest of this chapter has been organised as follows. In section I.2, we propose an updated definition of community energy based on the Scottish experience. In section I.3, we summarise and analyse the Scottish community energy sector, contrast it with some experience elsewhere in Europe, and include an overview of UK and Scottish government support mechanisms. Section I.4 gives an overview of the Chilean community energy sector, compares it to Scotland and uses concepts from game theory to analyse some of its main features. Based on this, section I.5 then presents some recommendations for Chile. Section I.6 concludes.

I.2 Community energy: towards an updated definition based on the Scottish experience

Before proceeding, it is useful to consider how community energy projects should be defined. The concept of community energy [35] has evolved through the years, reflecting a growth in terms of experience, knowledge and information, evidence, support from public and private entities, new and more transactions between communities and other stakeholders, newly available technologies, more regulations, and so on.

Of particular relevance to this chapter is the Scottish Government's definition, which defines community energy as "projects led by constituted non-profit-distributing community groups established and operating across a geographically defined community, including Bencoms"[8]. It then introduces another concept, "Locally-owned Energy", which includes "projects led by regional organisations which are not profit-distributing and have charitable aims such as housing associations and educational institutions or local authorities, as well as commercial businesses including farmers, land managers, rural small and medium-sized enterprises and profit-distributing co-operatives" [46]. It is

[8] Community Benefit Society, organisation created for serving the broader interests of a community. Members commonly have shares and democratic rights based on the concept "one member, one vote". Also, assets and profits must be used for the benefit of community.
See https://communityshares.org.uk/resources/handbook/community-benefit-societies

important to note that both definitions include an understanding in which community and locally-owned organisations carry out their mission and achieve objectives within a specific and well-defined geographic location, affecting a particular community or communities within a certain geographical range.

In order to have more information about the nature and characteristics of such projects, Van Veelen [61] develops a typology of 367 community energy projects in Scotland based on several variables, such as legal body, purpose, ownership, size of installation, technology, among others, defining five categories of projects. Within those categories, the study identifies 211 initiatives (often) described as development trusts, which are legally formed as a company often with charitable status and full community ownership; 63% of them (which had funding information available) had received economic/financial support from the government. On the other hand, only 20 projects are identified as energy cooperatives in which is possible to find projects from 1,000 kW of capacity. If development trusts are taken into account, it is possible to find projects only from 100 kW of capacity [61]. It is therefore clear that, in terms of the number of projects, development trusts are the dominant type of organisation considered by the Scottish people to be involved in energy production. Given that, one question emerges: what is a development trust?

According to the Development Trusts Association Scotland's (DTAS) definition, a development trust is an organisation that is [62]:

1. Engaged in the economic, environmental, and social regeneration of a defined area.
2. Independent, aiming for self-sufficiency and not for private profit.
3. Community based, owned, and managed.
4. Actively involved in partnerships and alliances between the community, voluntary, and private and public sectors.

DTAS [62] establishes that a development trust must meet all the four points mentioned before. Additionally, there is no specific legal/organisational structure for a development trust. However, most of the registered organisations in DTAS are companies limited by guarantee with charitable aims[9] and many have trading subsidiaries as well. It is important to note that a development trust is not necessary a “trust” in a legal sense [63]. Nevertheless, under these criteria, could a cooperative be considered as a development trust?

According to the International Co-operative Alliance’s definition and principles [64-67], a Cooperative is an autonomous association of persons united voluntarily to meet their common economic, social, and cultural needs and aspirations through a jointly owned and democratically-controlled enterprise. The members have an equal say in what the business does and a share in the profits. Comparing this concept with the DTAS’s definition of development trust, it is clear that the economic nature of a development trust and a cooperative are very similar, but there are some key differences. In a cooperative, the main goal is providing benefits to its members/owners [66,68,69], as result of the economic activity carried out by the cooperative entity, leaving to the community without a direct access to the profits or benefits. A cooperative is therefore not a charitable organisation [66,68]. Concerning this, SCENE [70] highlights that the primary motivation of community energy initiatives is “to generate local income and strengthen the local economy”, instead of providing benefits to the members of a particular project. Similarly, Van Veelen [61] notes that energy cooperatives in Scotland tend to be primarily motivated by the financial benefits their members might receive from participation in renewable energy, whereas development trusts’ primary motivation is generating local income. Another important difference is that a cooperative does not necessarily focus on a specific place because its members can belong to one or several communities within a small or big area, which is not necessarily well-defined. Hence, cooperatives do not meet at least two

[9] See http://www.communitycompanies.co.uk/charitable-companies-limited-by-guarantee

elements listed by DTAS so should not be treated as development trusts, even when both entities could seem indistinguishable in practice.

The information revealed above is useful to establish an updated definition of the concept of community energy based on the Scottish experience, due to the following reasons. Firstly, in the Scottish context, there are mainly two groups of initiatives, which people can use to participate in energy production, namely "non-profit-distributing community groups" or "community energy" per se, and "locally-owned energy". The main difference between them is related to the legal and organisational structure of projects, where the latter group does not distinguish between pro-profit and non-profit organisations[10]. Secondly, the first group seems to lead the community energy sector in Scotland, mainly through development trusts. Thirdly, energy cooperatives in Scotland are not important in terms of citizen participation in energy production, considering the number of projects. This is a key point in comparison with other countries like England, Germany, Denmark, etc., where energy cooperatives have a prevailing role [61,71-75]. Fourthly, as was shown before, an energy cooperative should not be considered as development trust so they should not be considered under the first group. This is important from a legal and economic perspective[11] [76].

Regarding the above, we propose the following updated definition of community energy, avoiding distinctions based on legal structures:

A community energy project (or initiative) is a project conceived, carried out, and implemented by people who are:

[10] It is important to note that, beyond the aforementioned classification, within the Scottish landscape of community energy projects it is possible to find different legal/organisational structures, such as companies with charitable status, transition towns, local environmental groups, community hall associations, among others. The above involve a variety of ownership models like, for instance, full community ownership, shared equity/joint venture, community shares, etc. [61].

[11] For instance, under the Scottish regulation, a community (group) can be eligible for all funding instruments, whereas other organisations, like bencoms and cooperatives, are eligible for all funding instruments unless they formally accept some rules, which shape the distribution of benefits. This would empirically demonstrate the different nature of cooperatives.

a) *Interested in generating energy.* We are not exclusively focused on renewable energy sources, as the current constraints on renewable energy use in terms of full availability of energy, capacity factors, utilization of storage devices, backup procedures in case of blackout, etc., still mean that fossil fuels have to play a role in some community energy projects.

b) *Located close to or in the exact place of the project*. This may seem to be a bit vague or imprecise. However, we think that it is necessary to highlight the existence of a geographical scope, without too strictly defining it, as an exact definition could depend on different aspects such as the current legal or regulatory framework, nature of the project, surrounding environment, technology, and many other factors, considering a range from just a few metres to many kilometres. For now, we therefore just note the existence of a scope in terms of geographical distance or area/place, as noted in Van Veelen [61]. This is coherent with the Scottish Government's definitions on these matters.

c) *Well-organised under any suitable legal and organisational structure.* This includes a formal definition of the rules, roles, and responsibilities of the project within the community and about their relations with other stakeholders.

d) *The owner or have a high participation in the ownership of the project*, as people should have the right to be involved in the project decision-making process, as well as obtain its benefits and assume its costs and risks. This point is directly related to the two underlying dimensions (process and outcome) of the concept of community energy stated by Walker & Devine-Wright [35].

e) *The main (and/or the first) beneficiary of the project.* This is related to the above-mentioned point. As long as people are the owner or have a high participation in the ownership of the project, they will have the right to get the project benefits before other possible participants in it. The outcome will then focus on people first, which is the essence of a community energy project.

f) *Primarily interested in welfare maximisation and income generation*, but in order to achieve other aims such as social and/or environmental goals, including an improvement in terms of local economy and energy independence. Here, the focus is not only on providing benefits to some members, but also the community as a whole.

Thus, at least from an economic perspective, a community energy project can be treated as an economic agent that receives assets from other economic agents, which must be managed appropriately, in order to obtain benefits to be invested in social initiatives or used to reach charitable aims. All of this is aimed at helping a community and gaining more (sustainable) independence. Considering this, in terms of energy production, this entity competes with other organisations, such as power generators and utilities. Therefore, more research is necessary in order to fully understand the community energy sector incumbents' incentives, economic behaviours, key differences, etc.

I.3 Community energy in Scotland

I.3.1 Specifics of community energy development in Scotland

Unsurprisingly, community energy and related concepts have been studied extensively. Some literature focuses on the organisational structure of community energy projects, trying to identify which conditions or elements are necessary for projects to be successful [35,36,77]. In addition, some literature focuses on remarkable cases, some of them based in Scotland. For instance, Warren & McFadyen [38] show that there was a kind of local 'affection' towards a windfarm from people in the Isle of Gigha, and note that the project faced less public opposition compared to similar projects in Kintyre peninsula. Rae & Bradley [78] note the importance of energy autonomy for communities and the success of community ownership in wind energy installations, considering a remarkable example in the Scottish village of Fintry. Bomberg & McEwen [37] identify that political conditions, which allow or constrain community energy projects, and non-material resources, which facilitate the functioning of community energy groups, mobilise community energy initiatives. They also highlight that a critical element is taking advantage of government resources and support, mainly through communities' knowledge, expertise, and connections. Additionally, the idea of survival, empowerment and autonomy, and income generation in a sustainable way as a main priority, contributed to the mobilisation of communities in energy production. Frantzeskaki et al. [55] note that a common feature in Scottish communities is the willingness to struggle for self-sufficiency and independence, which also applies to the energy sector. They also establish several categories of tensions that are faced by community energy projects, such as incompliant funding mechanisms, time-management and project management risks, financial viability risks, etc. Haggett et al. [79] find, for different stages of a community energy project, that economic motivations are the primary driver followed by control/autonomy, and environmental issues. In a more quantitative study, Seyfang et al. [49] find that the highest proportion of community energy groups in the UK operating in 2012 were located in Scotland, South West England, and South East England. Moreover, the area covered by community-related networks and organisations was higher in Scotland than England. Further stressing the importance of income generation, Okkonen & Lehtonen [80] apply Leontief's Input-Output Model to projects located in three Scottish archipelagos (Orkney, Shetland and the Outer Hebrides) and find positive impacts on employment derived from re-investments of revenues of community onshore wind power. More recently, Haf et al. [81] show the importance of confidence in the Scottish Government and its vision about the community energy sector by performing semi-structured in-depth interviews for four energy groups, including two groups located in the Scottish isles of Lewis and Tiree. They also note the disparity with some Welsh energy groups on these issues.

There is a significant amount of empirical evidence that would put the Scottish experience as a relevant and pertinent model to follow for other countries that may want to develop, deploy, and implement community energy projects, as can be seen above. Of course, that relevance is due to several factors, which include, among others, economic, environmental, historical, psychological and sociological aspects, such as desire for collective action, cultural milieu, and manifestations of community based actions in land reform. However, given that this is a multi-factorial problem, focusing on some key legal, economical, and statistical elements might be pertinent, ignoring other elements that are beyond the scope of this work. Some questions therefore emerge: how has the Scottish community energy sector evolved in recent years? Could the Scottish experience in community energy be comparable, in some aspects, with other countries' experiences? Is it possible to derive useful lessons from this evolution?

I.3.2 The evolution and some contrasts of the Scottish community energy sector

In 2011, official statistics show about 1.2 MW of installed capacity, mainly based on wind energy, from projects registered under the FIT scheme [44]. Similarly, since 2011, the EST has been working on reports related to the community energy sector in Scotland on behalf of the Scottish Government [45,82-87]. Regarding this, Fig. I.1. shows that projects labelled as "Community" reached 26 MW of installed capacity (366 installations) in June 2012 [82], whereas in June 2016, there were 510 installations adding up to 67 MW of capacity [86]. More recently, in 2018, 540 installations implied an installed capacity of 80 MW [45]. This therefore means an increase both in number and installed capacity during the last few years.

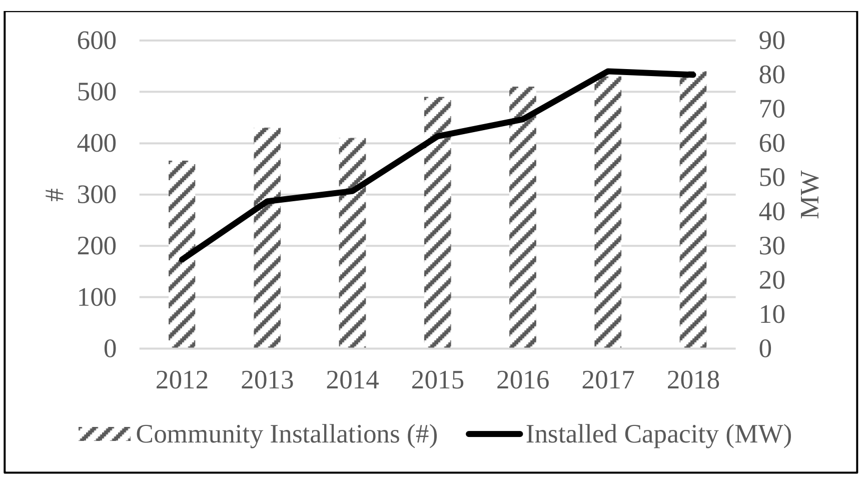

Fig. I.1. Operational installations and installed capacity of projects labelled as "Community"
Sources: [45,82-87]

We note that the installed capacity of these projects almost doubled during five years while the number of installations increased from approximately 400 to 540, implying that installations are, on average, larger than before. This evidence reveals a high level of growth in projects strictly led by communities. Based on the current data, in the next ten years, Scotland could see another 100 MW of installed capacity from this kind of initiatives, if the trend continues. This is a stark contrast with other countries where the participation of communities in energy production is still very weak, including, for example, Chile. In terms of energy sources, Fig. I.2. indicates that wind energy has been the preferred technology during the last years, followed by biomass, hydro, and waste-to-energy. The participation of solar PV technologies is relatively small in terms of capacity.

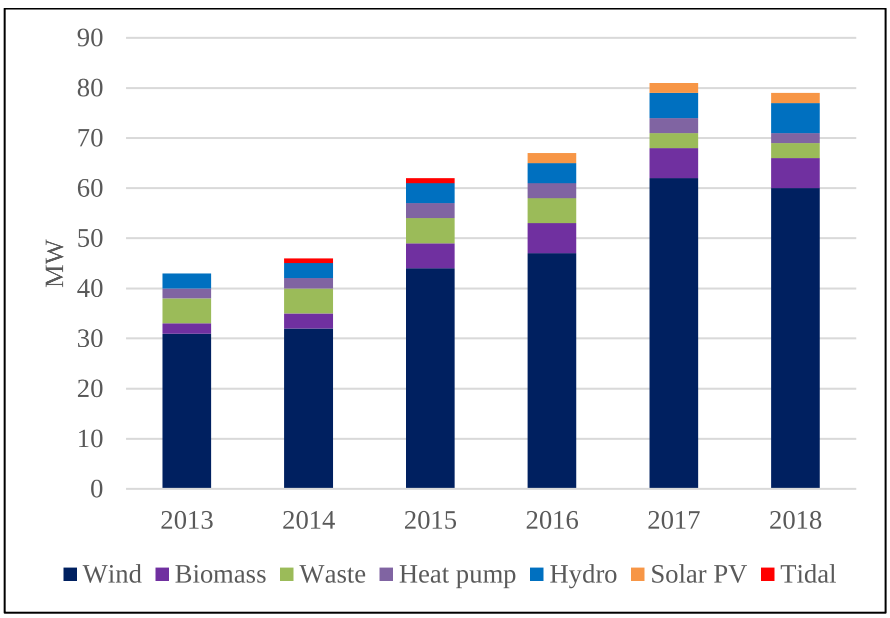

Fig. I.2. Installed capacity by technology of projects labelled as "Community"
Sources: [45,82-87]

If we also consider "local-owned energy" projects, the situation is even better. Table I.1. shows the minimum estimated installed capacity of this kind of projects, jointly with "community energy" projects. In 2016, the total capacity was 595 MW with an annual production of 1,479 GWh. This was a key milestone from a policy-making perspective, given that the Scottish Government in 2011 established a target of 500 MW of installed capacity by 2020, derived from these two types of projects [46-48]. In 2018, the total capacity reached 697 MW. Regarding this, the Scottish Government has set a new target of 1 GW derived from community and locally owned energy by 2020 [45].

Table I.1. Minimum installed capacity and annual expected production from community and local-owned renewable energy projects

Year	Minimum estimated community and locally owned renewable energy capacity (MW)	Minimum estimated community and locally owned electricity capacity (MWe)	Minimum estimated community and locally owned heat capacity including CHP and waste (MWth)	Annual expected production of renewable energy (GWh)	Annual expected production of electricity (GWh)	Annual expected production of heat including CHP and waste (GWh)
2012	204	88	117	489	233	256
2013	285	168	114	740	390	330
2014	361	202	159	895	470	425
2015	508	301	207	1,281	720	561
2016	595	354	241	1,479	840	639
2017	666	403	263	1,664	958	706
2018	697	432	265	1,755	1,051	704

Source: [45,82-87]

In order to achieve this target, the Scottish government has spent a significant amount of resources for implementing a variety of initiatives, mainly related to setting up a suitable legislation/regulation and proper incentives [46,88]. One of the most important initiatives is the CARES[12] [44,46,89,90] but there are also other relevant initiatives [90-92]. It is important to note that every single project has to demonstrate its economic and financial feasibility, and also show how the resources will be managed to benefit the wider community. Other aspects that are taken into account include management, impacts and costs, grid constraints, agreements between community and people involved in the project, etc. An expert panel decides about the resources that will be provided. Another feature of the community energy sector in Scotland is the participation of several organisations that provide useful support to communities, such as Community Energy Scotland[13], EST[14], Changeworks[15], SCENE[16], Local Energy Scotland[17], among others. However, not all is

[12] Community and Renewable Energy Scheme.
[13] See http://www.communityenergyscotland.org.uk/about-us.asp
[14] See https://www.energysavingtrust.org.uk/about-us
[15] See https://www.changeworks.org.uk/what-we-do
[16] See https://scene.community/our-work-overview
[17] Consortium made up of several organisations: EST, Changeworks, The Energy Agency, SCARF, and The Wise Group. This consortium manages the CARES.

perfect and some schemes complicate community energy projects. On this topic, Creamer [93], based on two-in-depth cases, notes that an incoherence between the length of the funding and the desired or expected outcomes in terms of CO_2 reductions and other positive lasting consequences, demanding administrative processes, and competition/rivalry for resources, might affect the development of such initiatives. Due to some changes in the CARES scheme in 2011, a key element has been the applicability and eligibility for the FIT scheme and the Renewable Heat Incentive, both introduced by the UK Government [46,94-96]. Under the FIT scheme, which was closed to new applications on the 31st of March 2019[18], there are some additional benefits for community energy initiatives and school installations, in terms of a relaxation of the minimum energy efficiency requirements and validity certification. These benefits also included the possibility of sharing a single grid connection and a tariff guarantee[19] [97]. Nevertheless, the aforementioned closure of this scheme might affect the development and deployment of community energy initiatives. Scotland has also developed a new Energy Strategy[20], which establishes a vision for the entire Scottish energy system up to 2050, taking into account three main themes: a whole-system view, a stable managed energy transition, and a smarter model of local energy provision [92].

Thus, it is clear that the incumbents of the Scottish community energy sector have been working in a suitable way, encouraging citizen participation in energy production by fostering and implementing projects that belong to either “non-profit-distributing community groups” or “locally-owned energy” categories. However, including recent evidence based on other experiences in Europe, in order to have a wider justification over the Scottish contribution to the community energy sector, seems appropriate.

Heras-Saizarbitoria et al. [74] note that approximately 3,000 energy cooperatives were already operating in Europe in 2014. However, almost 80% of these are located in

[18] See https://www.energysavingtrust.org.uk/scotland/grants-loans/renewables/feed-tariffs
[19] Available up to October 2015.
[20] It was available for public consultation.

Germany and Denmark. The cooperative sector involvement in energy production has been well described by Yildiz et al. [75] in the former country, where is possible to see classifications by value chain approach and technology, historical development, and regional development. Even when it is also possible to find other models of ownership, such as limited partnerships and civil partnerships, cooperatives are the most relevant organisational form regarding active participation in local energy policy [75]. Nevertheless, other European countries like the Netherlands and Sweden currently present a promising perspective. In the Netherlands, 500 initiatives were started by citizens and social groups during the last years, most of them related to the cooperative model [74]. In Sweden, there are currently 81 wind cooperatives, 6 solar PV cooperatives, 10 small-scale district heating producers, 25 eco-villages, and 9 rural communities owning renewable technologies. Additionally, in 2012, around 25,000 householders owned shares in energy cooperatives [73]. This suggests that energy cooperatives are the prevailing type of organisation for citizen participation in energy generation in Europe. Some evidence also shows the existence of other models, which allow involvement and/or ownership by public entities such as municipalities, private organisations including commercial developers or larger generators, and/or local citizens. Furthermore, state subsidies and tax reductions for micro-producers, net metering schemes, project shares sales, limitations on members' ownership, among others, have been deployed in order to boost citizen participation in energy production [73-75].

However, some of these policies could have adverse effects. For instance, Tews [98] notices that the auction scheme in Germany is a failure in terms of controlled renewable energy expansion, actor plurality, and cost efficiency, highlighting several issues: awards without construction permits, longer implementation deadlines, control exerted by a small number of professional project developers, and variation in prices.

Based on this evidence, we can highlight that Scotland has been strongly pushing energy generation projects led by citizens that aim to directly benefit communities as a whole, rather than only a certain number of people within a community. This might be crucial as investments in entities like energy cooperatives, made by people with sufficient savings to invest, might undermine social cohesion as some people miss out on project benefits [71]. In addition, from an economic perspective, if there is discrimination among the members of a cooperative, its viability might be affected, decreasing social efficiency and making the cooperative a weaker competitor [99]. However, as long as an energy cooperative benefits a community as a whole (or is incentivised to do so), the difference between these entities and community-led projects (such as development trusts) will be indistinguishable in practice. Further research is needed in order to empirically corroborate whether energy cooperatives are only providing benefits to their members and/or communities.

Nevertheless, the Scottish experience in community energy also has some negative or questionable aspects. For instance, it is true that the installed capacity of "non-profit-distributing community groups" (or community energy projects) is lower than the capacity of locally-owned energy projects. However, this difference may or may not be relevant, depending on the number of people who benefit from the project and whether the project benefits the community as a whole or not. This is important given that providing benefits for communities in a sustainable way is the main purpose of community energy projects. Therefore, some metrics might need to be developed in the near future, in order to determine the real contribution to the community energy sector and society from different types of organisations or structures. Additionally, there is such variety of specific legal and organisational structures available in Scotland (and, more widely, in Europe) that may or may not be considered part of the community energy sector. From a public policy perspective, this might be confusing, time-consuming, and demanding in terms of resources, especially for people who want to set up a community energy project. Hence, having fewer specific legal and organisational vehicles may be more convenient for all community energy incumbents. In fact, defining a kind of "Community-Special-Purpose Entity", following our proposed updated definition of community energy and unifying criteria derived from non-profit-distributing community groups and locally-owned energy projects, may be useful to reduce, among others, transactions costs.

In summary, weighing positive and negative features, we consider that the Scottish community energy sector might be considered as leader in citizen participation in energy production. Thus, countries with an underdeveloped community energy sector, including developing countries like Chile, should consider the Scottish experience as a relevant model when developing, deploying, and implementing policies aiming for a robust community energy sector.

I.4 Community energy in Chile

I.4.1 Chilean resource availability and electricity industry

The main feature that Chile and Scotland have in common is the high availability of renewable resources, which makes renewable community energy projects feasible.

For Chile, Santana et al. [100] show that the potential installed capacity of wind, from Arica to Chiloé Island, was 37 GW. In terms of solar PV energy, they show that the potential installed capacity for projects without a tracker[21] reached 1,238 GW, whereas for projects with a tracker[22], this reached 1,640 GW. In addition, the potential installed capacity of solar CSP[23] could be as high as 552 GW. The potential hydro energy capacity, considering some territorial constraints, was estimated at 12.5 GW with an average power of 7.8 GW. A 2009 Garrad Hassan study determined the potential capacity of marine energy[24], including wave and tidal. This study shows that the potential for raw offshore wave energy could reach 164.9 GW. For tidal energy, the estimated potential, in terms of

[21] Considering a capacity factor greater than 0.24.
[22] Considering a capacity factor greater than 0.3.
[23] Considering a capacity factor of 0.5 and 200 ha as minimum.
[24] Considering a single Pelamis wave farm of 30 MW of installed capacity in six locations (180 MW) between the fifth and tenth regions of Chile.

raw kinetic energy flux, was estimated between 0.6 and 0.8 GW [101]. However, only an area from Chiloé Island up to the Magallanes Strait would be interesting in terms of taking advantage of this energy source [102]. Chile also has biomass potential. In 2013, the Universidad Austral de Chile carried out a study[25], which found that biomass has a technically useful potential of up to 60,000 GWh/year, which implies an installed capacity of 2.1 GWe, based on the current consumption of native biomass [103].

These numbers are comparable to Scotland. In 2005, the Scottish Government published a study, which highlighted the potential of several renewable energy sources. An installed capacity of 16 GW, 1 GW, and 200 MW was estimated in this study for onshore wind, offshore wind, and hydro, respectively[26]. For biomass, a potential of 450 MW was estimated, mainly based on wood fuel resource and some energy crops. Marine energy (wave and tidal) was proposed as having significant potential with an installed capacity of 1,300 MW, considering suitable places located in the northern and western seaboards of the country [104]. Other investigations have been carried out and other similar estimations have been found in, among others, Andersen et al. [105], Allan et al. [106], and Neill et al. [107].

Table I.2. Estimated potentials of renewable energy per capita (kW/cap)[27] [28]

	Biomass	Wind	Solar	Hydro	Marine
Chile	0.12	2.05	121.73	0.69	9.2
Scotland	0.08	3.15	1.32	0.04	0.24

Sources: [100-104,108-110]

Hence, the availability of renewable resources in both countries is significant, as can be seen in Table I.2. Chile has huge potential in terms of solar, wind, and marine energy per capita. Likewise, Scotland also has enormous potential in terms of wind energy per capita,

[25] Between the regions of Coquimbo and Magallanes y la Antártica Chilena.
[26] This report emphasised the importance of small-scale projects and new improvements in current plants.
[27] Due to a scarcity of specific information related to the potential of solar energy in Scotland, an estimation very simple was made which considers the data revealed in Burnett et al. (p.341, 2014) about a baseline average resource of solar energy (W/m^2) and the Scotland's surface (km^2) available in the following website:
http://webarchive.nationalarchives.gov.uk/20160106191622/http://www.ons.gov.uk/ons/rel/regional-trends/region-and-country-profiles/key-statistics-and-profiles---august-2012/key-statistics---scotland--august-2012.html
[28] The population considered for Chile is 18,006,407 inh. and for Scotland is 5,400,000 inh. Both estimations are up to 2015.

although it is less well endowed with solar resources. This is one obvious reason that explains the current installed capacity of Scottish community energy projects, which is mostly dominated by wind projects. From this point of view, Chile could take advantage of its potential not only through projects carried out by large generators, but also, like Scotland, by encouraging community energy projects around the country, based on the variety of renewable sources that Chile has, and not solely on solar. This is relevant for Chile, considering that its current installed capacity is still mostly based on fossil fuels, as shown in Fig. I.3.

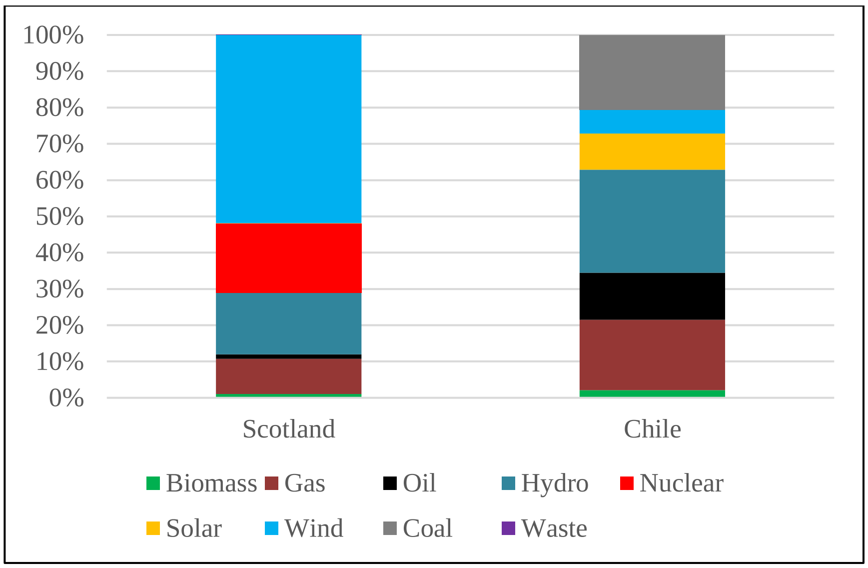

Fig. I.3. Scottish and Chilean installed capacity (of power plants) by technology currently in operation
Sources: [111,112]

On the contrary, Scotland's electricity mix is mainly based on renewable energy sources such as wind and hydro; still, it is currently encouraging community energy projects around the country, as discussed above.

I.4.2 Community energy in Chile: current status

Given that the Chilean renewable resources are at least comparable, and in some ways better than the Scottish resource, for instance, in terms of the energy per capita and the significant potential of solar and marine energy, it is necessary to further study the Chilean state of the art in terms of community energy initiatives in Chile. This may be useful to explore what has to be done to foster and deploy decentralised energy projects through community or citizen initiatives, which has been defined in the Chilean Energy Policy as one of the goals to be reached by 2050.

In short, this policy specifies in several ways that Chile needs a more intelligent electricity system, including a higher participation of citizens as producers/managers/consumers. All of this is aimed at having a more secure system that can face unexpected circumstances without major problems, and manages the energy required for users of the electricity system in a decentralized manner [40]. Apart from the resource availability and state of the art, we will analyse if Chile has similar definitions, views, and other elements as Scotland, or whether there are barriers related to resources availability.

In Chile, the concept of community energy is very new. In fact, citizen participation in energy generation has been deployed using a different approach. Instead of focusing on community energy, Chilean policy has focused on distributed generation. Considering Ackermann et al.'s [31] definition of distributed generation as "an electric power source connected directly to the distribution network or on the customer site of the meter", and our definition of community energy shown above, it is clear that both concepts are related. Distributed generation can be seen as a subset of the concept of community energy, because the former limits the scope to a distribution network and one single customer, and seems to be primarily based on technical aspects, whereas the latter is primarily based on economic and social aspects. Nevertheless, it is important to note that both concepts consider consumers as producers (prosumers), who need a network to inject the energy.

Following this idea, the Chilean government gave the right to individually generate energy/electricity for self-consumption through renewable energy or combined heat and power (CHP) sources to regulated customers (mostly residential clients)[29], through the Law 20,571 “Distributed Generation Law” [39], which includes the right to sell their surplus of energy to the grid [113]. In this sense, there were 24.41 MW of installed capacity operating under this law at December 2018 [114]. However, it is important to highlight that this amount includes not only residential installations, but also installations that might belong to small and/or medium businesses. In fact, if we only consider small systems (up to 10 kW or 0.01 MW), which represent almost 91% of the total installations that operate under this law, it is possible to see that these projects have only succeeded in installing 6.3 MW of installed capacity [114]. In addition, such projects are mostly based on rooftop solar energy and concentrated in the capital city and its immediate surroundings (Region Metropolitana), as noted in Fig. I.4. and Table I.3., and focused on individual generation and self-consumption rather than providing benefits to communities.

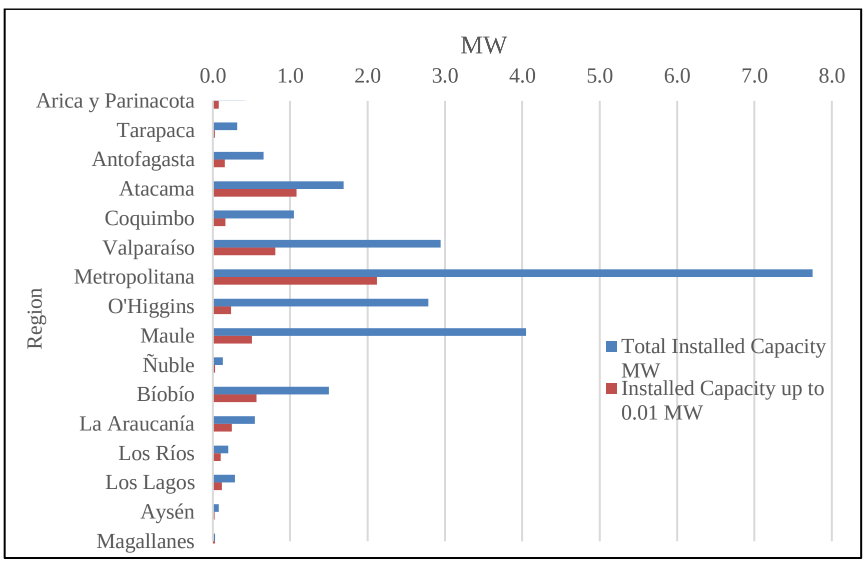

Fig. I.4. Distribution of distributed generation projects by region in Chile
Source: [114]

[29] According to the Chilean legal framework, defined as those clients who have a connected power below 0.5 MW or those clients that have asked for an authorization to be in this category (of regulated customers) having a connected power between 0.5 MW and 5 MW.

Table I.3. Installed capacity in MW of distributed generation projects by region and technology in Chile

Region	Biomass	CHP	Hydro	Solar	Total
Arica y Parinacota				0.42	0.42
Tarapaca				0.31	0.31
Antofagasta				0.66	0.66
Atacama				1.69	1.69
Coquimbo				1.05	1.05
Valparaíso				2.94	2.94
Metropolitana		0.05	0.09	7.61	7.75
O'Higgins				2.78	2.78
Maule			0.00	4.04	4.05
Ñuble				0.13	0.13
Bíobío				1.50	1.50
La Araucanía				0.54	0.54
Los Ríos				0.20	0.20
Los Lagos				0.28	0.28
Aysén	0.03			0.05	0.08
Magallanes				0.03	0.03
Total	**0.03**	**0.05**	**0.09**	**24.24**	**24.41**

Source: [114]

Hence, some questions remain. For instance, why do other regions with more potential for solar or wind energy have a lower implemented installed capacity? Is support from the government universally available and, most important, delivered properly? Is a shift in focus from distributed generation to community energy necessary in order to increase the number and capacity of projects conceived by citizens?

One important feature of the Chilean electricity market, as noted above and in [115], is that Chile has a net billing scheme, instead of a net metering scheme like other countries. Under the Chilean context, the concept of net billing means that the energy injected into the grid is calculated and valued at an injection rate (which is different from the consumption rate), and then the resulting value is subtracted from the cost of energy consumption (calculated as the energy consumption multiplied by the consumption rate). In the same vein, net metering means the energy injected into the grid is directly subtracted from the energy consumption, in kWh [116]. The main retail rate applied to most Chilean residential customers is the BT1 rate[30], which combines energy and capacity in a single rate, and consequently there is a difference between the rate of the energy injected into the grid and energy consumption. The rationale of this is that the injected energy has less

[30] Low Voltage 1, in Spanish.

value due to the utilisation of distribution infrastructure [115-117]. Conversely, under a net metering scheme the injected energy is valued at the same rate as energy consumption. Another important feature is that there is important divergence among cities in investment, tariffs or rates, capacity, and integration intervals, which means that payback periods for solar PV projects may vary from 6 years up to almost 17 years, depending on the location of the project [115]. In this sense, Becerra et al. [118] assess a wind farm in two different locations in Chile and note that it is possible to generate value from a regulation change. They also highlight that tax expenditures on support mechanisms could be better than a net metering scheme. Varas et al. [119] show that a net billing scheme in the northern part of the country could be profitable, if the investment cost is lower than 2,000 USD/kW[31]. Ramírez-Sagner et al. [120] highlight the fact that residential PV systems are more profitable under larger self-consumption rates.

As can be seen above, the net billing scheme is now an important element of the Chilean electricity market, so providing more insights by developing a simple example using game theory seems appropriate. We will do this in the next subsection.

I.4.3 The best strategies for Chilean residential customers under a net billing scheme

In order to provide a deeper and useful discussion about the convenience of implementing a net billing scheme, taking into account the Chilean experience, we develop a simple sequential non-cooperative game to demonstrate the effects of that scheme on Chilean residential customers, by determining Subgame-perfect Nash equilibria (SPNE). In this game, a consumer can decide whether to generate energy under the Chilean net billing scheme or not. If the consumer decides to do so, we then assume that the consumer buys a solar PV panel from the distributor, in agreement with the Chilean regulation. We

[31] According to the authors, this cost implies a solar PV plant size around 1 kW. If a net metering scheme was desired, the plant size has to be around 2 kW.

consider a solar PV technology useful life of 25 years [121] and representative investment costs for panels of 1 kWp, 2 kWp, and 3 kWp of capacity, which are USD 3,086.72, USD 4,948.06, and USD 6,188.95, respectively [122]. We then calculate representative annual amortizations of the investment costs for those panels, by using the following formulas [123]:

$$VP = C\left[\frac{1-\frac{1}{(1+r)^t}}{r}\right] \tag{I.1}$$

$$C = \frac{VP}{\left[\frac{1-\frac{1}{(1+r)^t}}{r}\right]} \tag{I.2}$$

Here, VP is the present value of the solar PV panel, C is the amount to pay under an annual basis during the useful life of the solar PV panel, r is the discount rate, and t is the solar PV technology useful life. We assume that a customer can amortize the whole investment during the PV technology useful life period. The resulting annual amortizations of the installed capacity (investment costs of solar PV panels) are shown in Table I.4.

Table I.4. Annual amortizations in USD of the investment costs of solar PV panels for residential consumers considering different discount rates and installed capacities

Discount Rate / Capacity	1 kWp	2 kWp	3 kWp
5%	219.01	351.08	439.12
7%	264.87	424.60	531.08
10%	340.06	545.12	681.82

The estimations for annual generation are 1,500 kWh, 3,000 kWh, and 4,500 kWh respectively, for the three aforementioned capacities [122]. The estimated annual generation can be valued using an electricity injection rate of 0.10 USD/kWh (valid in August 2017) and multiplying that injection rate by the production of each panel. The consumption rate, which is different from the injection rate, is 0.14 USD/kWh [124]. If we take the average consumption of a residential low-medium income consumer (LMIC), which is 1,800 kWh/year [115], and the same for a residential high income consumer

(HIC), which is 7,865 kWh/year [115], we can multiply the consumption rate by those average consumption levels to get gross costs.

The consumer therefore has to pay for its consumption and also for the investment cost of a solar PV panel, which will be annually amortized during the useful life mentioned above, minus the payment derived from the injection into the grid[32]. Thus, in this game, consumers and distributors can choose between to generate under a distributed generation scheme (G) or not to generate under distributed generation scheme (NG), and between to sell a solar PV panel (SP) or not to sell a solar PV panel (NSP)[33], respectively. An example is given in Fig. I.5.

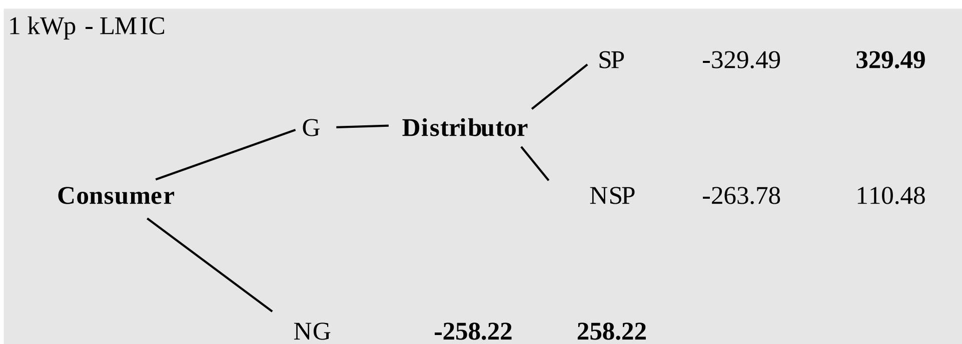

Fig. I.5. Sequential non-cooperative game solved by backward induction procedure for LMIC, considering 1 kWp of installed capacity and 5% as discount rate.

It is important to notice that every outcome revealed above is shown in USD per year and reflects the sum of the consumption per year, the investment for the solar PV panel amortized under an annual basis, and the annual payment for injecting energy into the grid.

In Table I.5., the SPNE for LMIC, HIC, and the distributor, considering different discount rates and installed capacities, are shown.

[32] Every value has been obtained considering an exchange rate of CLP 644.697649 / USD available in https://www.oanda.com/lang/es/fx-for-business/historical-rates.
[33] Under this strategy, consumers can buy solar PV panels from other sellers at a 30% cheaper rate.

Table I.5. SPNE for LMIC, HIC, and the distributor, considering different discount rates and installed capacities

Discount Rate / Capacity	1 kWp	2 kWp	3 kWp
10%	NG ; (SP, NG)	NG ; (SP, NG)	NG ; (SP, NG)
7%	NG ; (SP, NG)	NG ; (SP, NG)	NG ; (SP, NG)
5%	NG ; (SP, NG)	NG ; (SP, NG)	G ; (SP, NG)

Considering the assumptions listed above, the resulting strategies for LMIC and HIC (without brackets), and for the distributor (within brackets), which are also SPNE, producing energy under the current distributed generation scheme in Chile is not economical for consumers in most of the cases, due to the costs and potential benefits. Producing energy would only be an efficient strategy[34] for consumers if they amortize the initial investment during the whole useful life of the solar PV panel, if they can buy a device with a higher installed capacity (which is more expensive), and if they have low discount rates through those years, which are strong assumptions. If a consumer decides to generate energy in any other situation, that consumer would be harmed because its selected action would not be optimal given the choice made by the distributor[35].

Even if the investment costs are substantially lower, the conclusions are similar. Table I.6. shows a case where investments costs are reduced by 30% relatively to current rates.

Table I.6. SPNE for LMIC, HIC, and the distributor, considering different discount rates and installed capacities, and an investment cost 30% lower

Discount Rate / Capacity	1 kWp	2 kWp	3 kWp
10%	NG ; (SP, NG)	NG ; (SP, NG)	NG ; (SP, NG)
7%	NG ; (SP, NG)	NG ; (SP, NG)	G ; (SP, NG)
5%	NG ; (SP, NG)	G ; (SP, NG)	G ; (SP, NG)

Hence, these results might explain, at least in some sense, why residential consumers and distributors are not very interested in distributed generation schemes in Chile – the economics are just not favourable. A review of the incentives and how the current Chilean policies are addressing them is therefore necessary.

[34] It is important to note that payments for consumers are negative but less economically "harmful".
[35] This is because the consumer will lose more, as can be seen in Fig. 5.

I.4.4 Other specific initiatives

In 2014, the Chilean Government began a discussion about the associativity between communities and large generators, based on the following pillars: paying taxes where the power plant is located, price equality, and sharing benefits[36] [37]. However, the Chilean Government decided to push just the first two[38] [125,126]. The Chilean Government has also carried out other initiatives related to the concept of community energy. In particular, the programme named "Comuna Energética" seeks to increase citizen participation in the energy sector in every municipality. The programme focuses on renewable energy and energy efficiency projects, and comprises two main stages: the first one is a local energy strategy, and the second one is a certification process [127].

Some featured projects are related to energy efficiency, energy generation through solar PV panels, and energy usage/production awareness [128]. There is another initiative called "Fondo de Acceso a la Energía" which provides funding for small-scale solar PV projects in rural and isolated locations [129].

Taking the private sector into account, there are currently more than 20 cooperatives that are involved in the electricity market. Many of them are providing distribution services in rural zones. There is also an incipient initiative currently carried out by Fundación Proyecto Propio and Rubik Sustentabilidad[39]; private entities which seek to help communities conceive renewable energy projects with an installed capacity between 1 and 3 MW, contributing to the development of social projects in those communities. This initiative highlights the importance of establishing Power Purchase Agreements (PPA), to have a more sustainable source of benefits and carry out social projects in the community [130].

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[36] See http://www.nuevamineria.com/revista/proyecto-de-asociatividad-la-palabra-en-juego/
[37] See http://www.latercera.com/noticia/asociatividad-de-proyectos-de-energia-con-comunidades/
[38] See http://www.pulso.cl/empresas-mercados/gobierno-zanja-la-discusion-por-ley-de-asociatividad-y-divide-proyecto-en-tres-partes/
[39] See https://www.proyectopropio.cl/generacion-comunitaria/

The community energy sector in Chile is still incipient, as was shown before, but there are upcoming opportunities to improve this situation through proper policies that move the sector in the right direction, giving correct incentives to the economic agents. The Chilean renewable energy potential also offers a huge possibility to develop community energy projects. Thus, considering international experience, such as the Scottish experience in community energy, seems appropriate.

I.5 Discussion and recommendations

In the UK, and especially in Scotland, the community energy concept has been promoted explicitly and defined in a better way compared to several countries, including Chile. The definition and promotion of community energy sector in Scotland has been a catalyst in the deployment and implementation of a range of initiatives, including private and public supporting entities/organisations, grants and loans schemes, and so on. It is true that the community energy sector in Scotland is still a small part of the whole electricity sector in terms of installed capacity. But, at the same time, the growth that the community energy sector has undergone in recent years is remarkable. Moreover, the range of projects has been wide; although the main energy source has been wind, there are also significant levels of other renewable sources. In addition, energy cooperatives (private profit organisations) do not have such significant role, and more social organisations like development trusts, seem to be leading the community energy sector in Scotland, considering the number of projects. Conversely, in mainland Europe, energy cooperatives seem to lead the community energy sector, but it is not clear if these entities are providing benefits to some members or communities. This is a key element, because the essence of a community energy project is providing benefits to communities and not only to some members. Therefore, Scotland should be recognised as a worldwide example in community energy development.

On the contrary, despite the fact that Chile has more potential in terms of renewable energy, Chilean public policies on this matter seem weak and contradictory, especially, if we consider that the scope up to now seems focused on the promotion of distributed generation projects. Distributed generation is a more specific concept, related to the concept of community energy, but not always convenient for residential consumers and distributors. This has resulted in several deficiencies, such as a geographical concentration of projects, a small installed capacity derived from those initiatives, and a mix based exclusively on just one renewable energy source. One critical aspect has been the difference in tariffs between the injection and consumption of energy by residential consumers, even when there might have been technical reasons for this. This is a challenge for Chilean policymakers. In this sense, a change in tariffs could be one of the main opportunities for Chile to help the community energy sector.

Beyond this, considering the specific legal/organisational structures available in Chile seems crucial. In this sense, it seems that in Chile more existing social and collaborative organisations, like neighbour committees and indigenous communities, could take an important role to push citizen participation in energy production [131], particularly community energy rather than distributed generation projects.

Still, how could these projects face potential asymmetries in terms of treatment in comparison with other incumbents of the Chilean electricity market? We theorise that generation as a PMG[40] could be a path forward. A PMG is a project connected to the network, which has less than 9 MW of excess capacity, has the right to be exempt from transmission costs, and is subject to the electric system operator [132]. It can avoid the gap between injection and consumption tariffs. If the PMG is connected to the distribution network, that project is catalogued as a PMGD[41]. If these projects have an installed capacity up to 3 MW, they are not subject to an environmental assessment[42], which could

[40] Small Generation Source, in Spanish.
[41] Small Distributed-Generation Source, in Spanish.
[42] See https://www.sea.gob.cl/sea/proyectos-actividades-sometidos-eia

help to push these initiatives in a faster way. This is relevant considering that most of them are focused on generating energy on the basis of renewable energy sources.

Additionally, considering the evidence presented above, a community engaged with a certain type of generation project is a minimum requirement in order to carry out projects successfully. Support from the government, as well as other entities would enable an increase in people's involvement and knowledge, in terms of management and other skills necessary to deal with community energy projects. This is critical due to the size of these projects, the variety of disciplines involved, the diversity of backgrounds and skills, etc.

Even though community energy organisations have more social objectives than many firms, a primary motivation is still profit maximization, which then helps to achieve other objectives that benefit the community's development. This profit maximization is demanding, but it is what helps to communities gain more economical (understood as a variety of resources including energy) independence in a sustainable way. In the long-term, this also helps governments to save and manage resources in a better way. To achieve profits, the specific legal or organisational structure does not matter significantly, but skills do, and it is very important that organisations remain focused on profit maximization, in order to help the whole community.

Altogether, the establishment of a thriving community energy sector in Chile requires rethinking the electricity market with a major component of decentralised generation, through community energy instead of distributed generation. We therefore make the following recommendations:

1. Review the current narrative around distributed generation and its promotion, considering current (and future) incentives and gaps, in order to improve uptake, or (preferentially) change the focus towards a broader concept such as community energy.

2. Explicitly define long-term objectives in relation to community energy projects.
3. Review tariff structures and prepare a pathway to adapting a legal and regulatory framework to support community energy projects, avoiding negative impacts on electricity markets.
4. Consider giving priority to the development of community energy projects as a PMG or PMGD with an installed capacity up to 3 MW, given that most of them will be based on renewable energy sources. This might avoid extra costs and delays due to bureaucratic procedures and potential conflicts like public opposition, for instance.
5. Analyse the current electricity network and design a long-term roadmap, in order to incentivise the reinforcement of the grid to support the connection of these projects, if necessary.
6. Carry out more research, especially addressing sociological issues, in order to know more about Chilean communities and discover who would like to be involved in community energy initiatives.
7. Foster the independence of communities, developing and delivering skills and tools in order to properly manage community energy projects in the future, through new private and public supporting entities.

I.6 Conclusions

This chapter has discussed the Scottish experience in community energy development, considering the main evidence available up to now. The Scottish experience should be recognised as a worldwide example of how communities are trying to deal with several issues, including increasing economic independence through renewable energy projects. Obviously, it has faced and still faces important challenges, but also opportunities. With the support of a range of private and public entities, communities are currently taking advantage of these opportunities.

In comparison, the Chilean community energy sector is weak and incipient. This is mainly due to the Chilean government's support towards distributed generation schemes instead of community initiatives in energy production, even when that would not be convenient for consumers under the current net billing scheme. However, given the potential in terms of renewable resources, geographical conditions, communities, etc., a wider community energy deployment is possible in the medium or long term, if this is supported with explicit government policies. This will present an enormous challenge, because it challenges the way electricity markets are currently operating. Nevertheless, based on their nature, community energy projects could be an effective tool to tackle climate change, increase the renewable energy participation in the electricity mix, and improve the economy and quality life of communities. This chapter aims to be a first step in getting a deeper understanding of this phenomenon, building on the Scottish experience to derive useful recommendations. More research will be necessary in the near future to help Chile and other developing countries to develop a thriving community energy sector.

II. AN EXPLORATORY ASSESSMENT OF PREFERENCES FOR LOCAL SOLAR PHOTOVOLTAIC ENERGY INITIATIVES AND THE EXPLICIT INCLUSION OF OWNERSHIP MATTERS

II.1 Introduction

During the last few years, Chile has been pushing many renewable energy initiatives across the country, based on its significant potential of renewable resources. Several authors through different studies have explored Chile's potential availability of renewable energy sources. For instance, Santana et al. [100] highlight the significant wind, solar photovoltaic (PV), concentrated solar power (CSP), and hydro energy potential. Furthermore, Garrad Hassan estimates significant potential for marine energy, including wave and tidal energy [101], which could be used along the Chilean coast. In the same vein, the Universidad Austral de Chile notices the potential for biomass that could be part of the renewable energy mix [103]. Although the Chilean generation mix is still strongly influenced by fossil fuels, their participation is steadily decreasing. One example of this transition is the rise of solar PV initiatives in Chile, which grew from nearly zero to over 2 GW between 2012 and 2018, considering only large-scale installed capacity[43]. In reality, the installed solar capacity is larger, as small and medium scale solar PV initiatives have also been set up throughout the country. For example, in December 2018, the capacity of solar PV-based installations with an installed capacity up to 10 kW or 0.01 MW, reached 6.3 MW [114]. Most of these projects consist of rooftop solar PV panels on residential houses and small and/or medium businesses. Moreover, these initiatives are focused on individual generation and self-consumption and very concentrated in the capital city and its immediate surroundings [114]. Despite this, the increase of small and medium scale solar PV initiatives cannot be denied. In fact, one key factor behind this growth is the promulgation of Law 20,571 named the "Distributed Generation Law" or "Net Billing Law" [39], which gives regulated consumers the right to individually generate

[43] See https://www.greentechmedia.com/articles/read/explaining-latin-americas-impending-solar-boom1

energy/electricity for self-consumption through renewable energy or combined heat and power (CHP) sources. This includes the right to inject any surplus of energy to the grid [113]. However, as noted in Fuentes González et al. [133], this scheme might not be convenient for residential electricity customers, and other forms of citizen participation in energy generation schemes may be more effective options.

Beyond the dilemma about which scheme could be the best one for residential electricity customers, the Chilean government has already set out clear objectives. A document called "Ruta Energética 2018-2022" specifies one key goal in relation to this matter: the achievement of four times the current installed capacity of distributed small-scale renewable generation (with a size less than 300 kW) by 2022 [134]. This reflects ongoing calls for a more profound citizen participation in energy production. However, one question arises: even when there is an increasing level of commitment from different stakeholders for promoting citizen participation in energy production, do people really want to participate in such initiatives?

This chapter attempts to provide answers to the aforementioned question by gathering information, through a web-based survey that considers a Likert scale, and using data analysis techniques to better understand the implications of this question. We analyse whether people are willing to devote money and/or time to solar PV-based citizen energy projects, and investigate which specific variables influence such willingness. For respondents' simplicity, we do not make specific comparisons between different types of citizen participation in energy production schemes such as net billing schemes or community energy projects; rather we use the wider concept of local solar energy initiatives based on solar PV (LSIPV). LSIPV might provide a means for inclusive and sustainable decentralised energy production growth for a wider number of people. It encompasses a wide range of projects that vary in, for example, project developer, ownership model, level of community engagement, etc. Thus, LSIPV include community energy projects, net billing or net metering schemes, energy cooperatives, and other initiatives. This wider definition therefore facilitates the information collection process, as well as the respondents' tasks. Focusing on Region Metropolitana, Chile, where 40% of the Chilean population resides [135], we collected attitudinal and stated preference data to assess willingness to devote money and/or time to LSIPV and the main variables influencing such willingness. Our main goal is to provide an enhanced understanding of customers' interest in and perceptions of LSIPV, which can then in turn facilitate the implementation of public policies that enable markets to align with these preferences, business models that are more likely to be accepted, and educational strategies pertaining to local solar PV.

Although, as outlined below, there is existing literature on this topic, one particularly novel contribution of this study is the inclusion of 'sense of ownership', i.e. the degree to which citizens perceive to be owners of the project. As we show, this is an important variable that helps explain attitudes towards LSIPV, which has now been included in previous studies.

The remainder of this chapter has been organized as follows. In section II.2, we present the theoretical background behind this study. Section II.3 outlines the methodology used to carry out this study. Section II.4 shows the results. In section II.5, a discussion and some recommendations that follow from the results are given. Finally, section II.6 concludes.

II.2 Theoretical background

As mentioned above, the concept of LSIPV involves a variety of initiatives related to citizen participation in energy production, and hence, the relevance of the determinants, barriers, and boosters of people's willingness to participate in, by devoting time and/or money, goes beyond the current European and Chilean context. For example, in the United States, carrying out a survey considering fuzzy logic inference model, Zhai & Williams

[136] find that the perceived cost is a main factor influencing customers' decision to purchase solar panels, but also show that perceived maintenance and environmental concerns have significant impact. Rai & Beck [137], using survey data, note that perceived affordability is the strongest predictor of consideration of solar PV and intention to call a solar provider. On the other hand, solar technology was perceived (even by those with higher than average educational attainment) to be more costly than it was in reality. Similarly, Farhar & Coburn [138] reveal that financial gain, along with environmental benefits, was one of the highest-scoring perceived benefits of grid-tied PV in a survey of Colorado homeowners. In the same vein, community solar program administrators identified the main challenges to implementing their projects, as determining a subscription model that would meet potential participants' needs, finding subscribers willing to put money into purchasing shares and members to participate, selecting and securing a site, among others [139]. Of course, the European experience also offers many studies that deserve to be mentioned here. For instance, Seyfang et al. [49], through a web-based survey, find that 71% of the respondents (community energy groups) develop solar PV-based generation activities and that the main objectives for such groups are saving money on energy bills, reducing CO_2 emissions, improving energy independence, community empowerment, and generating income for community. Hicks & Ison [140] model the motivations driving community energy projects considering several cases in different continents, including some solar PV-based projects in Scotland and Germany. Broughel & Hampl [141], based on a two large-scale representative surveys and focused on Austrian and Swiss community energy projects, model the profile of potential investors noting that respondents are willing to invest from 1,000 to 10,000 CHF/EUR in such projects, and one of the most promising technologies in this sense is solar PV. Bauwens [142] establishes the determinants of the members' investment size for two energy cooperatives, of which one of them develops solar-based projects. Dóci & Vasileiadou [143] study projects in Germany and the Netherlands and find that aspects such as decreasing energy costs, addressing climate change, and some hedonic motivations, influence investments in renewable energy projects at community level, including

initiatives based on solar PV. Salm et al. [144] segments two groups of community energy investors showing their preferences and expectations, and find that solar PV is the most popular technology among them. At a broader level, in relation to the variables that may influence people's willingness and interest in citizen-led energy production initiatives, Kalkbrenner & Roosen [145] notice that social norms, trust, environmental concern, and community identity are influential in determining willingness to participate in community energy projects. Bauwens [146] reveals that the activation of social norms might foster investment decisions in community renewable energy initiatives, based on data from cooperatives in Belgium. Koirala et al. [147] show, using a survey carried out in the Netherlands, that environmental concern, renewables acceptance, energy independence, community trust, community resistance, education, energy related education, and awareness about local energy initiatives are the most important factors in determining the citizens' willingness to participate in community energy systems. In a more qualitative study, Koch & Christ [148] establish that the main drivers for participation in an urban solar PV project in Switzerland are the desire to support local renewable energy and feel a sense of project ownership at little effort or expense. They also highlight that the initial financial investment is a barrier for half of the interviewees who chose not to participate in.

As can be seen above, although there is substantial evidence that financial incentives are a key determinant of willingness to engage with LSIPV, there are also many social determinants and variables. There is a clear need to understand these better, particularly in the Chilean context which is likely to differ from Europe and the US. Based on the literature discussed above, we hypothesize that there is a set of variables that influence residential customers' willingness to participate in LSIPV by devoting time (WTDT) and/or money (WTDM). This includes, firstly, social variables that may play a key role in establishing the necessary relationships among the members of a community that facilitate people's participation in LSIPV. Secondly, given that our focus is on renewable energy, specifically solar PV energy, we expect that people's environmental concerns may influence their participation in LSIPV. Thirdly, we expect that people with a more technical awareness, even when this feature is based on perceptions rather than facts, may influence their WTDT and WTDM to LSIPV. Lastly, some economic and demographic features may also influence people's participation in these kinds of initiatives.

In addition, we notice that there is no explicit reference or consideration to ownership matters in most of the evidence shown above. Ownership matters are very important as they might define which particular scheme a person would like to be involved with. For example, a high/strong sense of ownership could indicate that citizens would like to be involved in a more individual citizen participation in energy production scheme like a net billing project, whereas a low/weak sense of ownership would mean the opposite, which would lead the choice of a community energy project. To investigate this, for the purposes of this work, we include a specific variable called "sense of ownership" in order to corroborate its significance and influence on WTDT and WTDM to LSIPV. This variable is an attempt to capture the level to which people feel that they own a project, which, we hypothesize, implies a willingness or desire for making decisions about that project, assuming the benefits, costs, and risks derived from owning it. In summary, the variables that we expect to affect electricity residential customers' WTDT and WTDM to LSIPV are shown in Table II.1.

Table II.1. Variables that hypothetically would affect electricity residential customers' WTDT and WTDM to LSIPV in Region Metropolitana, Chile.

Type of variable	Variable
Social	Community identity Trust Willingness to collaborate with community in a LSIPV Perceived community interest in solar energy
Environmental	Environmental concern
Socio-technical	Desire for energy independence Sense of ownership Perceived usefulness of solar PV technology Perceived solar energy profitability Buying solar technology expertise
Economic	Property Ownership Electricity Payer
Demographic	Education Income Age Gender

Taking into account these variables, we perform an online survey, followed by a regression analysis of the resulting data to better understand which variables influence respondents' WTDT and WTDM, as well as the main barriers to participate in LSIPV. The details of the corresponding methodology are shown in the next section.

II.3 Methodology

This study uses an online survey to collect data and analyse electricity residential customers' perceptions of solar energy and their willingness to participate in LSIPV by devoting time and/or money (WTDT and WTDM). The target respondents for this online survey were electricity residential customers who are 18 years old or older and live in Region Metropolitana, Chile. Respondents were recruited through collaboration with local organizations, which disseminated the online survey link via their websites or social media platforms. This means that we use accidental sampling; the implications of this are discussed at the end of this chapter. Random sampling, which would have been preferred, is not possible here. However, the 99 valid responses we received do include respondents from a wide range of backgrounds. In Table II.2., the main respondents' demographic and socio-economic characteristics are shown.

Table II.2. Main respondents' demographic and socio-economic characteristics.

Features	Sample Frequency (N=99)	
	Count	%
Gender		
Male	49	49%
Female	49	50%
Other	1	1%
Age		
18–24 years	3	3%
25–29 years	5	5%
30–39 years	32	32%
40–49 years	24	24%
50–64 years	22	22%
65 years and older	13	13%
Highest education level		
Secondary school or below	6	6%
Technical schooling centre	6	6%
Professional institute	6	6%
Undergraduate degree	32	32%
Postgraduate degree (Master's or PhD)	49	50%
Average monthly net household income (amounts in USD) [44]		
Less than 415	3	3%
415 – 720	2	2%
721 – 1,257	5	5%
1,258 – 2,194	14	14%
2,195 – 3,825	25	25%
3,826 – 6,674	22	22%
More than 6,674	19	19%
I don't know/prefer not to say	9	9%
Rent vs Own (self or family)		
Owner	80	81%
Renter	19	19%
Type of dwelling		
Stand-alone house	32	32%
Semi-detached home	27	27%
Flat	38	38%
Other	2	2%
Who is paying electricity bill?		
Respondent	73	74%
Someone else	26	26%

The online survey was designed considering the existing literature on solar energy adoption and community energy experiences, as discussed above. It consisted of several sections. First, we provided a brief description of solar PV panels' features and various ways in which individuals may participate in LSIPV. Respondents were then asked for information on the variables listed in Table II.1, which we hypothesised to influence an individual's WTDT and WTDM to LSIPV. The respondents were then asked a number of

[44] The exchange rates considered for all calculations are USD/CLP 619.6 and USD/GBP 0.758 according to OANDA.com.

questions with seven-point Likert scales that aimed to capture the different determinants of the WTDT and WTDM discussed above. These questions, as well as their summary statistics and measurements of internal consistency within these determinants are listed in Tables II.3. and II.4. References to previous studies using the same or adapted questions are listed in the final columns of these tables, where appropriate.

Table II.3. Two-items-based and three-items-based variables, their corresponding sources and measurements of internal consistency.

Question/Item & Variable	Item-Total Correlation	Source
Perceived usefulness of solar PV technology		
— I consider solar PV panels to be a reliable technology	0.751	[136, 149]
— I think using solar PV panels to produce electricity is beneficial for the environment	0.751	
Cronbach's Alpha	0.857	
Spearman-Brown Coefficient	0.858	
Buying solar technology expertise		
— I feel that I know enough about solar energy technology to make an informed purchase decision	0.791	-
— I feel that I know enough about solar energy technology market (suppliers) to make an informed purchase decision	0.791	
Cronbach's Alpha	0.880	
Spearman-Brown Coefficient	0.883	
Community identity		
— I consider my community to be a good place to live	0.561	[145,150]
— There are many people in my community whom I think of as good friends	0.809	
— I feel attached to my local community	0.821	
Cronbach's Alpha	0.848	
Spearman-Brown Coefficient	-	
Sense of ownership		
— If I were to participate in a local solar PV initiative, it would be important to me to directly influence decisions related to the project	0.710	-
— If I were to participate in a local solar PV initiative, it would be important to me to directly assume the benefits, costs, and risks of the project	0.710	
Cronbach's Alpha	0.831	
Spearman-Brown Coefficient	0.831	
Environmental concern		
— I am concerned about environmental issues (e.g. climate change, depletion of natural resources, water scarcity, etc.)	0.794	[137]
— I am concerned about the environmental impact of my home's electricity consumption	0.794	
Cronbach's Alpha	0.881	
Spearman-Brown Coefficient	0.885	
Perceived solar energy profitability		
— I think using solar energy would save me money	0.673	[149, 151]
— I think using solar energy would help to protect my home from rising electricity prices in the future	0.673	
Cronbach's Alpha	0.804	
Spearman-Brown Coefficient	0.805	

Table II.4. One-item-based variables and their corresponding sources.

Question/Item & Variable	Source
Desire for energy independence	
— It is important to me to be more energy independent at home and, at the same time, less reliant on my energy (utility) company	[139]
Trust	
— I assume that people in my community have only the best intentions	[152]
Perceived community interest in solar energy	
— Solar energy is a topic of interest in my neighbourhood	[151]
Willingness to collaborate with community in a LSIPV	
— I am willing to collaborate with others in my community to develop a local solar PV energy initiative	-
Willingness to participate in LSIPV by devoting time (WTDT)	
— How is your willingness to invest time in a local solar PV initiative?	[145,147]
Willingness to participate in LSIPV by devoting money (WTDM)	
— How is your willingness to invest money in a local solar PV initiative?	[145,147]

As can be seen in Table II.3., all results for Cronbach's Alpha present a value over 0.8, which denotes that our key variables are internally consistent. Nevertheless, among some researchers there is some controversy about the benefits of the Cronbach's Alpha for variables or scales formed by two questions [153]. We therefore also include the Spearman-Brown formula for two-item-based variables. The resulting Spearman-Brown coefficients are greater than 0.8 in all two-items-based variables, so we can assume that the internal consistency of our variables is acceptable. Based on these results, we compute for all variables shown in Table II.3 an average score among questions that belong to a specific variable, in order to maintain the same scale. As already mentioned, most questions in Tables II.3. and II.4. are adapted from previous work. In most of the cases, the original scale was altered to a seven-point Likert scale and questions about "Perception of profitability" include an "I don't know" response option. People were also specifically asked about their WTDT and their WTDM to LSIPV, considering only one seven-point Likert scale question for each one of these dependent variables.

Regarding the 'sense of ownership' concept, our questions were based on existing literature on ownership issues. This includes Lachapelle & McCool [154], who refer to the concept of ownership as a shared sense of problem and process to address wicked situations. It also involves association of citizens and agencies to collectively define, share, and address problems with redistribution of power. More specifically, Lachapelle [155] defines sense of ownership considering three questions: 1) who has a voice and whose voice is heard? 2) who has influence over decisions and what results from the effort? 3) who is affected by the process and outcome? Marks & Davis [156] establish, in a study about rural water systems in Kenya, a scale of sense of ownership based on several elements, such as feeling about being an owner, family involvement as owners, members' involvement as owners, and a concern about the operation and maintenance of such systems. As noted before, Koch & Christ [148] find, for some interviewees, emotions related to the concept of sense of ownership, in a study where interviewees felt positive feelings about being like co-owners and energy producers rather than mere customers. Hence, the concept of sense of ownership involves several elements including the existence of an objective (problem) to be reached (solved) through a coordinated process with coordinated efforts (participants); also, an effective participation and recognition (voice); and decision-making processes with their results and/or consequences. Following this literature, we operationalise 'sense of ownership' through two questions: one about the perceived importance of having a direct influence over decisions and the second one about the perceived importance of facing/taking all consequences, i.e. all benefits, costs, and risks derived from LSIPV.

In the next section of the survey, participants were asked to indicate the main barrier, from their perspective, to participate in a local solar energy initiative, choosing from several alternatives. Finally, participants were asked to provide information on their gender, education level, housing type, whether they own or rent a dwelling, whether they or someone else pays the electricity bill, and income. These factors will be explored for their potential influence on respondents' WTDT and WTDM (or WTP) to LSIPV. Housing type and home rental vs. ownership are particularly relevant as individuals who are not homeowners would be generally unable to install solar PV devices.

In terms of data analysis, we first analyse descriptive statistics for all independent and dependent variables considering the entire survey group. The scores from the respondents' answers are then used to determine the most significant variables that might affect WTDT and WTDM to LSIPV, by estimating a multi-variate linear regression model using IBM SPSS version 20®. This model is estimated considering all variables shown in Table II.1. Given that we do not have specific hypotheses about magnitude, order, and direction of the relation and significance of each independent variable (for these respondents), we then perform the backward selection method to select the significant variables and corroborate the results performing the enter method.

II.4 Results

II.4.1 Descriptive statistics

Descriptive statistics are listed in Table II.5. below. As can be seen in this table, respondents on average have a "high" environmental concern (with mean 6.06 and standard deviation 1.44), perceived usefulness of solar PV technology (with mean 6.08 and standard deviation 1.49), and desire for energy independence (with mean 5.97 and standard deviation 1.65). Respondents' sense of ownership reaches a mean 5.26 with standard deviation 1.58 and trust presents a mean 4.86 with standard deviation 1.49. Community identity has a mean 5.20 with standard deviation 1.46. It is interesting to note that the lowest score and highest dispersion is obtained by the "buying solar technology expertise" variable, which has a mean 3.29 and standard deviation 1.85.

Table II.5. Descriptive statistics for variables that hypothetically would affect electricity residential customers' WTDT and WTDM to LSIPV

Type of variable	Variable	N	Mean	SD
Social	Community identity	98	5.20	1.46
	Trust	99	4.86	1.49
	Willingness to collaborate with community in a LSIPV	99	5.61	1.71
	Perceived community interest in solar energy	99	3.76	1.77
Environmental	Environmental concern	99	6.06	1.44
Socio-technical	Desire for energy independence	99	5.97	1.65
	Sense of ownership	99	5.26	1.58
	Perceived usefulness of solar PV technology	98	6.08	1.49
	Perceived solar energy profitability	99	5.70	1.42
	Buying solar technology expertise	98	3.29	1.85

In terms of respondents’ WTDT and WTDM to LSIPV, according to Table II.6., the first variable presents a mean of 5.41 with a standard deviation 1.53. The distribution of the respondents’ scores indicate that most of them are willing to devote time (76.8%) and the rest are neutral or more unwilling to do so. The second variable reaches a mean 4.78 with a standard deviation 1.52. The distribution of the respondents’ scores indicate that 61.6% of the respondents are willing to devote money to LSIPV but a considerable rise of indecisive people can be noted at the same time (24.2%).

Table II.6. Respondents’ WTDT and WTDM to LSIPV

N=99	Very Low	Low	Slightly low	Neutral	Slightly high	High	Very High	Mean	SD
WTDT (%)	4.0	1.0	6.1	12.1	18.2	32.3	26.3	5.41	1.525
WTDM (%)	6.1	2.0	6.1	24.2	30.3	18.2	13.1	4.78	1.522

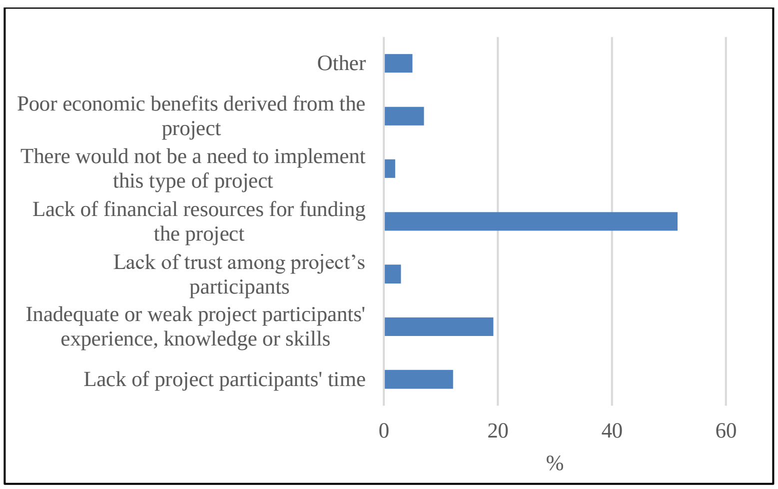

Fig. II.1. Main barriers for respondents to be willing to participate in a LSIPV.

Fig. II.1. shows the main barriers for the respondents to be willing to participate in a LSIPV. As can be seen here, the most important perceived barrier is “lack of financial resources for funding the project” (more than 50% of the choices). It is followed by “inadequate or weak project participants’ experience, knowledge or skills” (about 20% of the choices), and “lack of project participants’ time” (nearly 15% of the choices).

II.4.2 Regression Analysis

As shown below in Table II.7., the regression model explains a significant part of the variance (adjusted $R^2 = 0.287, F(4) = 10.759, p < .001$) in WTDM to LSIPV, confirming the validity of our model. The standardized coefficients show that the most important variable is willingness to collaborate with the community in a LSIPV ($\beta = 0.461, p < .001$), followed by community identity ($\beta = -0.301, p < .05$), sense of ownership ($\beta = 0.266, p < .05$), and Education - Postgraduates v/s Secondary school or below ($\beta = -0.256, p < .01$). The rest of the variables, namely trust, perceived community interest in solar energy, environmental concern, desire for energy independence, perceived usefulness of solar PV technology, perceived solar energy profitability, buying solar technology expertise, house ownership, electricity payer, education (other categories), income, age, and gender are not significant and, therefore, they are not included in Table II.7. After checking the case-wise diagnostics and residuals statistics, we find six potential cases to be catalogued as influential or outlier. Nevertheless, none of these six cases presented a Cook's distance greater than one, so we conclude there is no outlier that justifies a removal.

Table II.7. Significant coefficients of the regression analysis for WTDM

	Unstandardized Coefficients		Standardized Coefficients
	B	Std. Error	Beta
Constant	2.884^{***}	.545	
Community identity	$-.314^{*}$	.125	-.301
Sense of ownership	$.256^{*}$	.107	.266
Willingness to collaborate with community in a LSIPV	$.409^{***}$	.117	.461
Education (Postgraduates v/s Secondary school or below)	-1.626^{**}	.550	-.256

Dependent Variable: WTDM
*** p < .001
** p < .01
* p < .05

As can be seen in Table II.8., the regression model explains an even larger fraction of the variance (adjusted $R^2 = 0.506, F(6) = 17.541, p < .001$) in WTDT to LSIPV. The standardized coefficients show that the most important variable is willingness to collaborate with community in a LSIPV ($\beta = 0.808, p < .001$), followed by sense of ownership ($\beta = -0.220, p < .05$), trust ($\beta = -0.206, p < .05$), buying solar technology expertise ($\beta = 0.180, p < .05$), house ownership ($\beta = -0.167, p < .05$), and electricity payer ($\beta = -0.167, p < .05$). The rest of the variables, namely community identity, perceived community interest in solar energy, environmental concern, desire for energy independence, perceived usefulness of solar PV technology, perceived solar energy profitability, education, income, age, gender are not significant and, therefore, they are not included in Table II.8. After checking the case-wise diagnostics and residuals statistics, we find six potential cases to be catalogued as influential or outlier. Nevertheless, again, none of these six cases presented a Cook's distance greater than one, so we conclude there is no influential case or outlier that justifies a removal.

Table II.8. Significant coefficients of the regression analysis for WTDT

	Unstandardized Coefficients		Standardized Coefficients
	B	Std. Error	Beta
Constant	3.278***	.493	
Buying solar technology expertise	.150*	.063	.180
Trust	-.211*	.084	-.206
Sense of ownership	-.213*	.092	-.220
Willingness to collaborate with community in a LSIPV	.722***	.087	.808
House Ownership (Owner = 0, Tenant = 1)	-.658*	.289	-.167
Electricity payer (Respondent = 0, Someone else = 1)	-.575*	.248	-.167

Dependent Variable: WTDT
*** $p < .001$
* $p < .05$

II.5 Discussion and recommendations

As the results above show, on average, respondents have a high score for all variables, with the exception of two variables: perceived community interest in solar energy and buying solar technology expertise. This suggests that the respondents might not have enough knowledge about what their neighbours think about solar energy development, which would denote a need for improving the communication among neighbours, if an increased citizen participation in energy projects is desired. This may imply a cultural change that may take a huge effort, but should be possible. Moreover, respondents do not think or feel they know enough to buy solar energy technology. This means that the government and/or private sector should strengthen the current communication channels and deploy an effective marketing strategy that targets potential customers of solar energy technologies, especially taking into account that there would be a potential market to explore, as respondents would be willing to participate in LSIPV. In terms of trust and community identity, both variables are closer to the "neutral" score. In this sense, the government should deal with this matter by encouraging and facilitating communication as well as deeper connections or relationships among the neighbours of a particular community. Of course, all of this does not exclusively depend on specific activities carried out by some public or private entity; rather, there are more profound cultural, psychological, historical, and sociological aspects that also need to be properly addressed in the context of LSIPV emergence. This might take longer, but it should be considered and promoted, especially in the context of community energy emergence in Chile.

We can also highlight that respondents in this study on average have a high WTDT but a lower WTDM, in comparative terms, even though they are, on average, higher educated and have a higher salary than the average Chilean consumer. Interestingly, the most important perceived barrier to LSIPV is "lack of financial resources for funding the project", which indicates either (real) financial constraints or just reluctance about spending money on LSIPV. Most people in our sample have undergraduate and/or postgraduate degrees (82%), which indicates reasonable access to financial resources and a better wage, so it appears that respondents are not necessarily credit-constrained but are reluctant to spend money on LSIPV, even though they realise that financial constrains are the most important barrier to these initiatives. This suggests that better knowledge of, and access to, schemes that provide funding and/or reduce risk would be beneficial. It also suggests that information about the potential returns to investment in LSIPV might be lacking. Another interesting result to note is that, even when people are willing to spend time on LSIPV, they are worried about the project participants' time, so here the focus should be on promoting an equal participation of people in such initiatives. At the same time, improving and strengthening people's expertise should be a priority, at least, at a basic level that is enough for knowing the project management main aspects. It is not necessary for all participants to have comprehensive knowledge about all aspects of LSIPV project management, but a better distribution of tasks and knowledge of what goes on in the project may help address the perceived issue of lack of time put in by other project participants.

Nevertheless, according to the aforementioned results, respondents are on average willing to participate in LSIPV. Of course, the next question is how (or alternatively, through which scheme) would people participate in LSIPV? We encourage further research in this sense for Chile, particularly addressing social elements like sense of ownership as mentioned beforehand.

Concerning the regression analysis results, we can highlight that willingness to collaborate with the community in a LSIPV, community identity, sense of ownership, and education (postgraduates v/s secondary school or below) are significantly related to WTDM to LSIPV. Willingness to collaborate with community in a LSIPV offers the largest positive contribution to WTDM, which is expected. On the other hand, the largest negative contribution to WDTM is given by community identity. This might be explained by the fact that respondents in our area of study, which is mostly urban, do not have a strong identity or attachment with their closest community or group of neighbours. However, they might be willing to collaborate with others by devoting money only if they develop a specific initiative with others (community), such as a LSIPV. It is also possible that areas with a stronger community identity differ from the others in other ways (e.g., in disposable income) and are therefore less interested in LSIPV. In the same vein, when respondents report a lower education level, they are less willing to give money, which can be seen through the coefficient for education (postgraduates v/s secondary school or below) – this is likely to be a wage effect, as respondents with a lower education level are more likely to be credit-constrained. Finally, sense of ownership is positively related to WTDM, as we expected. As explained above, respondents that want to make decisions and assume benefits, costs, and risks (derived from a LSIPV), are likely to be more engaged with the project, may get additional utility from playing their part in it, and may also perceive lower risks, as they have some measure of control over the project; all of these effects would lead to a higher WTDM.

In terms of the second regression model, we notice that willingness to collaborate with community in a LSIPV, sense of ownership, trust, buying solar technology expertise, house ownership, and electricity payer are significantly related to WTDT to LSIPV. Willingness to collaborate with community in a LSIPV offers the largest positive contribution to WTDT, as it does for WTDM, which is expected. Buying solar technology expertise is the second positive contribution to WTDT in terms of magnitude. This might indicate that respondents with knowledge about what, how, and where to buy solar technologies, would be willing to contribute to LSIPV by spending time and delivering their knowledge. Respondents with a lower perceived level of knowledge may feel that they cannot usefully contribute to LSIPV. The coefficients for house ownership and electricity payer negatively contribute to WTDT indicating that when respondents are not the owners or are not paying the electricity bill, they are not willing to spend time in a LSIPV; this is straightforward. Trust is also negatively related to WTDT and this might be explained by the fact that respondents that trust others would rather spend time on other activities, leaving project management to others. In the same vein, sense of ownership negatively affects to WTDT – the opposite of its effect on WTDM. This is somewhat puzzling, but may be explained by the fact that respondents who want decision-making power and carry some of the project risks are less willing to, in addition, spend time managing the day-to-day running of the project.

Based on the above, some recommendations can be derived that could help encourage the emergence of citizen participation in energy production initiatives:

1. Foster deeper communication and connections within the communities and inform people in these communities about the advantages of energy production initiatives.
2. Give more information about solar energy technologies as well as the opportunities that energy/electricity markets could provide for people.
3. Provide clarity on access to funding and encourage transparency within the project about the sharing of risk and effort.
4. Delve into and analyse more social elements (especially taking the concept of sense of ownership into account) that may influence WTDT and WTDM, broadening the scope and collecting more representative data from Chilean residential customers.
5. Design and implement specific tools based on social and/or economic variables, for example, that help people to decide which scheme would be the best for them. This can be seen as an analogy of the customers risk profiles for financial investments, made by some financial companies.
6. Define specific and verifiable policies (and procedures) for promoting citizen participation in energy production jointly with Chilean communities.

II.6 Conclusions

In this chapter, the question about whether people would like to participate in energy production based on solar PV initiatives was addressed from a social science perspective. Most respondents are willing to participate in these projects by devoting time and/or money. We have identified social factors, recognised in the state-of-art literature, that influence this willingness, including trust, willingness to collaborate with the community, community identity, buying solar technology expertise, among others. We also include the concept of sense of ownership in an explicit way and show that this influences customers’ willingness, although not always in the expected way. Despite their willingness, respondents are worried about how such projects would be funded, how people can obtain and develop the necessary knowledge for managing the projects, and the effective time that people contribute to the project.

Our sample is small and not entirely representative for the entire Chilean population. For instance, in our sample respondents have a higher educational level, live in flats in a higher degree and in houses in a lower degree, and the female proportion is a bit lower[45]. This could lead to different results. People with a lower educational background might not know the main implications of (using) solar PV technologies and also present some complications at the time of devoting money, as they would perceive a lower income. On the other hand, in Chile most people live in houses so this could facilitate the installation of generation devices and then affects WTDT, WTDM, and the independent variables. Moreover, there could be other factors or variables that might influence or affect WTDM, WTDT, and other variables, which could have been omitted in this work. Of course, social science offers one perspective to deal with these matters, but there are other approaches like decision theory, choice theory, and game theory, for instance, that may also offer proper answers to such problems.

Nevertheless, based on the exploratory nature of this study, we think these results should encourage further research in order to generalize the results to the Chilean population. Such research with a more profound analysis can provide better results and conclusions that can also be generalised to the population, which may strengthen the current public policies of citizen participation in energy production in Chile and then develop a thriving community-led energy production sector tackling climate change and improving local economies in a sustainable way. This could be possible via having community energy projects across the country.

[45] See http://www.censo2017.cl/microdatos/

III. THE PROMOTION OF COMMUNITY ENERGY PROJECTS IN CHILE AND SCOTLAND: AN ECONOMIC APPROACH USING BIFORM GAMES

III.1 Introduction

Citizen participation in energy production is increasingly becoming an important matter in many countries around the world. This is evidenced by the fact that the number of news items, reports, scientific articles, dedicated public and private organisations, and projects that are related to or involved in this matter, is steadily increasing. Moreover, this concept is also progressively playing a major role in governments' decisions, through a variety of public policies, laws and regulations that have been or are being implemented; an important example is article 16 on local energy communities in the European Union's electricity directive[46]. Unsurprisingly, the corresponding installed capacity of citizen-led electricity generation projects has increased remarkably during the last few years, especially in some European countries like Scotland [45,82-87]. There are other countries, like the Netherlands, Spain, and Sweden, which show similar trends. Additionally, Germany and Denmark deserve mention, as these countries represent a model to follow given the nature and number of projects and their contribution to the generation mix [73-75]. These experiences can be used to encourage and help other less developed countries, like Chile, in promoting and implementing their own citizen-led projects in energy generation. In fact, the Chilean Government has explicitly declared its willingness to support a more decentralised system and a higher participation of citizens in energy markets as prosumers, rather than mere customers [40,133].

Under the broad umbrella of citizen participation in energy production, it is possible to find a wide variety of initiatives, such as community energy projects [35,36], distributed generation projects [31], locally-owned energy projects [46], projects based on hybrid

[46] See https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52016PC0864&from=EN

partnerships (with public, private, and/or civil involvement) [75], among others. Of course, the diversity of projects will depend upon the specific context in each country or energy market.

For the purposes of this chapter, the focus will be on community energy projects. These initiatives are examined and contrasted, in the sense of economic-strategic viability, with other well-known schemes; specifically, distributed generation projects and regular utility contracts. Accordingly, in this work a regular utility contract is understood as an ordinary electricity provision contract between a customer and a distributor/supplier. A distributed generation project is defined as "an electric power source connected directly to the distribution network or on the customer site of the meter", following the Ackermann et al.'s [31] definition. As noted in Fuentes González et al. [133], a community energy project is defined as a project conceived, carried out, and implemented by people who are:

- Interested in generating energy
- Located close to or in the exact place of the project
- Well-organised under any suitable legal and organisational structure
- The owner, or have a high participation in the ownership, of the project
- The main (and/or the first) beneficiary of the project
- Primarily interested in welfare maximisation and income generation.

The same authors notice that community energy projects are more complex than distributed generation, in terms of their nature and characteristics, because the former do not need to be connected to distribution networks, can involve more than one customer at the same time, and imply not only technical aspects, but also social and economic ones [133]. As a consequence, community energy projects should guarantee to their members proper cooperation mechanisms and attractive incentives to join and remain a part of the project. Moreover, community energy projects should be competitive compared to other ways of energy production, which should imply higher benefits for their members, as well as a long-term sustainability. These characteristics imply a dual behaviour of community energy projects because, on the one hand, these projects need cooperation and, on the other hand, these initiatives need to compete with others projects. As far as we are aware, there are no existing studies that model such dual behaviour from an economic-strategic perspective.

Game theory appears as a suitable tool to analyse this setting. Game theory can be defined as a discipline that aims at determining the best possible outcome and the corresponding strategy (or set of actions) to get to this outcome, for a number of decision-makers (players) who interact in a particular situation or context (game). Game theory also allows finding out what the players' incentives are and whether they are aligned and affected by any stimulus that might imply changes (instability). In principle, games can be cooperative, where players cooperate with each other, and non-cooperative, where players do not cooperate but make their decisions individually to maximise their own objectives. There are also hybrid games, which consider cooperative and non-cooperative behaviour at the same time. Although these have, to our knowledge, not been applied to energy markets, we suggest that they are especially appropriate to model the dual behaviour of community energy initiatives, and will apply them in what follows.

There is a variety of hybrid games. This chapter is focused on a simple and intuitive approach called biform games theory [157,158], which, as we will show, can be applied to electricity markets and the community energy sector. Adapting the existing literature on biform games, we formulate simple and novel three-player games that model two residential electricity consumers with a high and low/medium average electricity consumption, respectively, and a distributor or supplier that provides electricity to both consumers. We apply these games to data from two countries, Scotland and Chile, as community energy projects have been significantly promoted in the former and distributed generation schemes in the latter. For each of these two countries, we therefore analyse three scenarios: a base scenario in which consumers buy electricity through regular utility contracts, a scenario where community energy projects are pursued, and one where a net billing distributed generation scheme is in operation. In all of these, all players interact with each other.

This chapter aims to make three specific contributions. First, by using biform games theory, we develop simple but pioneering examples taking into consideration real data from Chile and Scotland, in order to better understand the community energy sector, its economic-strategic viability and the interaction with other projects or schemes. The economic-strategic viability concept means that an initiative or project provides the best possible payoff or outcome for the incumbents, given a feasible and rational strategy (or set of actions). The best possible payoff or outcome can be seen as either monetary losses or monetary benefits, depending on the circumstances and results of the modelled situation. By addressing these metrics, we can derive insights about the stability inside the projects (or coalitions) and competitiveness with other schemes, which can help policy makers encourage a thriving community energy sector through proper long-term public policies that are compatible with the energy market incumbents' incentives. Second, we derive some lessons that can help people distribute a payoff or outcome among the members of a community energy project. Third, this chapter aims to show another way of thinking about community energy projects, considering a methodology that is not currently widely used for the analysis of electricity markets and the community energy sector. This can contribute to a further dialogue between game theorists and energy modellers, which will help increase the deployment of community energy initiatives and a deeper penetration of renewable energy sources.

Since we are mainly concerned with demonstrating a new method and deriving qualitative insights, our models are highly simplified and we make a number of restrictive assumptions. Most importantly, we focus exclusively on the economic-strategic side of community energy initiatives. We recognise that there are other elements that might affect people's decisions and/or behaviour, which we do not include, such as psychological, sociological, historical or environmental factors. These could be included in more realistic models, at a price of reducing model transparency and increasing computational cost.

The remainder of this chapter is organised as follows. In section III.2, we present the theoretical background necessary to build up the biform games. In section III.3, we reveal the main features and assumptions of our approach based on biform games. In section III.4, the results are shown. In section III.5, a discussion of those results is given. Finally, section III.6 concludes.

III.2 Theoretical background

III.2.1 State-of-the-art analysis of the community energy emergence

A community energy project implies cooperation among the members, which is particularly crucial. People with different feelings, motivations, attitudes, judgement, professional background and experience, points of view, etc., need to agree with others in order to successfully carry out and implement the project. Many studies show the importance of the social-institutional elements in the emergence, constitution, and operation of community energy projects [36-38,52,55,79,81,145-147,159-161]. Additionally, because these initiatives are currently playing a role within liberalised electricity/energy markets, other studies characterise the (potential) incumbents of the community energy sector, as well as the market and its characteristics [49,54,60,71,72,74,141-144,162-164].

Fewer studies focus specifically on economic-financial aspects. In one study, Leontief's Input-Output Model is applied to Scottish community energy projects to evaluate their impacts on the local economy [80]. Lakshmi & Tilley [165] determine the Return on Stakeholders' Capital (RoSC) and Cost of Stakeholders' capital (CoSC) for a particular community energy project in England, for the purpose of monitoring and improving its functioning, regardless the scale. Berka et al. [56] calculate the expected Net Present Value (NPV) and Levelized Cost of Energy (LCOE) for community-owned projects at different development stages, and show the existence of higher costs, longer project development times, and higher risks, in comparison with commercial projects.

In relation to the economic-strategic viability of projects, Abada et al. [166] analyse an energy community, understood as an initiative where several households in a given building decide to use a single meter and potentially cooperate and install solar photovoltaics (PV) panels. They point out that there is no assurance that coalitions of households will be viable, and that this is affected by the installation costs, coordination costs, and sharing rules. Lo Prete & Hobbs [167] show how microgrid development affects costs and benefits for network incumbents (a utility company, a private investor in microgrids, and residential customers), highlighting market failures, the importance of microgrid introduction timing, and effects on prices. Lee et al. [168] analyse the cooperation between small-scale electricity suppliers and end-users in direct trading, proposing a fair pricing and revenue division scheme for them. There are also other studies that propose resources allocation schemes in different contexts [169-172]. More recently, Abada et al. [173] highlight the interaction between energy communities and a distribution system operator and the effects derived from the grid tariff structure.

Hence, it seems that the prevailing trend has been to analyse the social-institutional features of community energy projects, principally dealing with psychological, sociological, historical, institutional, and/or political factors, in order to find out which category or categories significantly affects the emergence and success of community energy projects. Consequently, we can find relevant information about people’s attitudes and willingness towards community energy projects, the impact derived from particular public policies, the features of such projects that might help to clearly define community energy, and so on. Most of the aforementioned studies use statistical and social sciences techniques. On the other hand, the economic-financial side of the community energy emergence has received less attention, which indicates an opportunity to properly delve into this matter, for instance, by developing more advanced valuation models of such projects, new ways of funding, more knowledge about a suitable cash flow management, etc. Concerning the last group of studies related to the economic-strategic viability, it is important to highlight two elements of interest: firstly, most of these studies are based on cooperative game theory, where in essence players form coalitions to get the best possible payoff or outcome and distribute it among them, ensuring stability. The basic idea is to assure that the members will remain in the coalition. Competition between community energy projects and other existing schemes is not considered in these studies. Secondly, these investigations take into account projects that are closer to or under the above-mentioned definition of distributed generation than that of community energy, mainly because the focus is on specific buildings and/or dwellings within these, rather than proper small or medium-scale power plants owned by communities. Also, the strategic interactions chiefly occur at the distribution level. This is not a sine qua non condition for community energy projects.

Thus, from our perspective, there is a gap that deserves to be appropriately explored in terms of modelling community energy projects and their interactions with other schemes or projects, in order to find clues that may help to answer the following research questions: a) is it possible to assure stability within a coalition that allows its members to remain in and then contribute to the emergence of community energy projects?; and b) is it possible to know more about whether a community energy project is attractive for its members in comparison with other schemes or projects?

III.2.2 Biform games fundamentals

Community energy projects present a dual behaviour: cooperative on one side, where the members of a community energy project need to cooperate with each other in order to carry out the initiative; and non-cooperative on the other, where the project itself competes with other projects or schemes of electricity/energy provision. As mentioned above, such dual behaviour can be modelled by using hybrid games. Examples of hybrid games and their variety of applications can be found in several studies. For example, Grossman & Hart [174] apply a two-stage hybrid game, with non-cooperative and cooperative stages, and show that one firm purchases another one when the former's control increases the productivity of its management more than the loss of control decreases the latter's management productivity. Similarly, Hart & Moore [175], also using two-stage hybrid games, address the dilemma of when transactions should be fulfilled within the firm or through the market. Taking a more technical view, Zhao [176] establishes an intermediate non-cooperative and cooperative solution concept for n-person games, considering one stage and deriving cooperative games from non-cooperative games. Ray & Vohra [177] study binding agreements in which each player's payoff depends upon all other players' actions. As can be seen, these studies are highly theoretical, developing game-theoretic methods rather than applying them to specific industries or incumbents.

Within the hybrid games theory literature, biform games form a specific category. A biform game [157] consists of a hybrid game (cooperative and non-cooperative) that employs the core (second game stage) and Nash equilibrium (first game stage) as solution mechanisms, which are developed under a common methodology. The link between both stages is represented by a confidence index, which is derived from the Hurwicz criterion and subsequent modifications [157,178,179]. Accordingly, a biform game can be formally defined as follows [157]:

$$(Z_i, \dots, Z_n; V; \alpha_i, \dots, \alpha_n) \tag{III.1}$$

where:

Z_i is a finite strategy set for each $i = 1, \dots, n$ player.
z_i is the player i's selected strategy.

V is a map from $Z_i \times \ldots \times Z_n$ to the set of maps $P(I) \rightarrow \mathbb{R}$, with $V(z_i, \ldots, z_n)(\emptyset) = 0$ for every $z_i, \ldots, z_n \in Z_i \times \ldots \times Z_n$.
α_i is the player i's confidence index, which is between 0 and 1.

The resulting set of strategies $z_i, \ldots, z_n \in Z_i \times \ldots \times Z_n$ defines a transferable utility game with characteristic function $V(z_i, \ldots, z_n)$: $P(I) \rightarrow \mathbb{R}$, where $P(I)$ is the set of all subsets of the players set I. This means that, for each coalition $S \subseteq I$, $V(z_i, \ldots, z_n)(S)$ is the value created by coalition S, given that the players choose the strategies $z_i, \ldots, z_n$. Thus, to solve a biform game, it is necessary to follow five steps [157]:

1. Determine the core for the cooperative part or second stage of the (biform) game.
2. Calculate the range of payoffs for each player.
3. Use α_i and $(1 - \alpha_i)$ to compute the weighted average in order to evaluate the cooperative part of the game, applying that index to the largest and smallest payoffs that every player could receive.
4. Assign to player i a payoff equal to the i's weighted average, in order to reduce the cooperative stage to a non-cooperative game.
5. Compute the Nash equilibrium of the non-cooperative part or first stage of the game.

There are several applications of biform games to economic and strategic problems. For instance, Stuart [180] analyses the newsvendor problem and determines the equivalence of the inventory decision to a capacity decision under Cournot competition, considering scenarios with uncertainty and no uncertainty. The same author, in [181], by using biform games, notices that in a monopoly, competition only partially determines the outcomes affecting the monopolist's capacity decision. Ryall & Sorenson [182] study whether a broker, who intermediates between two or more parties, has a competitive advantage and whether this could persist. Hennet & Mahjoub [183,184] go over the supply network formation considering it as a biform game instead of cooperative linear production games. From a more technological perspective, Kim [185] develops adaptive cognitive radio spectrum sensing/sharing algorithms for smart grids, based on biform games. Jia [186] models endogenous investments in assets, which have made to support a specific relationship, and examines how those investment decisions may change due to competition and governance arrangements. Feess & Thun [187] analyse the surplus division in supply chains on investment incentives, taking into account the Shapley value instead of the core in the second stage. Li & Chen [188] describe the relations of competition and cooperation on innovation networks by using biform games. Considering biform games, Menon [189] highlights the fundamental role of cognitive elements on strategic interactions and develops the core components of strategic mental models. To our knowledge, there are no existing applications of biform games to the community energy emergence, despite this being a useful tool to model the dual cooperative and competitive nature of community energy projects.

Based on the studies mentioned above, it is worth highlighting the flexibility that biform games can provide in terms of (potential) applications, which might help to deal with different situations where is possible to find cooperation and competition at the same time. This is not only related to the economic and strategic fields, but also to other disciplines such as engineering, as developed in [185]. Given this flexibility, biform games allow obtaining deeper knowledge about stability, or how a community-led project can incentivise and retain the membership, by giving information about the players' negotiation power that comes from the cooperative stage of each game without considering procedural assumptions of bargaining. In addition, through the non-cooperative stage it is possible to get information about whether a strategy is good and creates a favourable cooperative stage for players, where they have the chance to negotiate and then obtain the best possible payoff or outcome [157]. All of this might help to better understand the emergence of community energy projects, as well as the related cooperation mechanisms and the competitiveness of such projects, which can be translated into economic-strategic viability. As noted above, the focus of the existing literature on community energy has been on a more social and institutional view, leaving the financial and economic perspective aside from the main stream of analysis, so our approach enriches the current knowledge on community energy development and biform games applications.

Biform games take into account the Nash equilibrium as the solution mechanism for the first (non-cooperative) stage, which is defined as follows: the strategies $(z_i^*, \dots, z_n^*)$ are Nash Equilibria if, for each player i, z_i^* is player i's best response to the strategies $(z_1^*, \dots, z_{i-1}^*, z_{i+1}^*, \dots, z_n^*)$ chosen by the other players that solves the following optimisation problem [190]:

$$max_{z_i \in Z_i} f_i(z_1^*, \dots, z_{i-1}^*, z_i^*, z_{i+1}^*, \dots, z_n^*) \qquad \text{(III.2)}$$

The function payoff, f_i, is given by the cooperative part or second stage of the game. To solve it, biform games take into account the core as the solution mechanism. The core is defined as follows [191,192]:

$$C(v) = \{x \in \mathbb{R}^n | \sum_{i \in I} x_i = v(I), \sum_{i \in S} x_i \geq v(S) \, \forall \, S \in P(I)\} \qquad \text{(III.3)}$$

In words, the core can be defined as a mathematical methodology to distribute payoffs or outcomes among the players, in which the sum of all payoffs of each player i ($\sum_{i \in I} x_i$), who belong to the players set I (also referred as grand coalition), has to be equal to the coalitional value of I, $v(I)$, represented by a characteristic function v. This is sometimes called the efficiency principle. Additionally, the sum of all payoffs of each player i who belong to coalition S ($\sum_{i \in S} x_i$), has to be greater than or equal to the coalitional value of S, $v(S)$. This is called coalitional rationality. This applies to all coalitions that belong to the coalition set $P(I)$, including single coalitions. Consequently, any payoff allocation or distribution agreement under the core is stable, in the sense that no player can achieve a higher payoff outside a coalition within the core [192]. Mathematically, the core can be non-empty (feasible solution) or empty (infeasible solution), as shown in Fig. III.1.

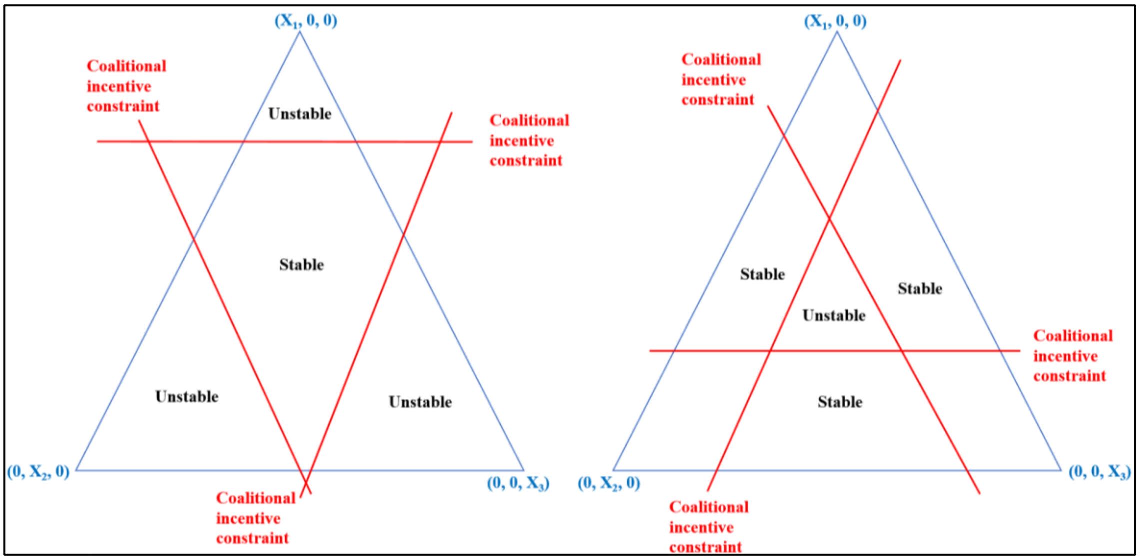

Fig. III.1. Non-empty and empty core
Source: adapted from [74]

Fig. III.1. represents a way to plot the core by drawing a triangle in barycentric coordinates[47], in which the plane of the plot is $\sum_{i \in I} x_i = v(I)$ and drawing each point on the plane at which the three coordinates sum to $v(I)$. Then, the coalitional incentives constraints are drawn on the plane, in order to find which points are stable or unstable. Moreover, to find games with an appropriate and feasible solution, the core has to meet three mathematical conditions at the same time, according to the Bondareva-Shapley theorem: superadditivity, convexity, and balancedness [192-195].

The link between the first and second stages of the biform game is the parameter α_i, which is the player i's confidence index. This index can be seen as a representation of the players' beliefs about the fraction of the coalitional value they could capture in the cooperative part of the game. We can therefore obtain information about the degree of competition and potential bargaining opportunities. This is why the confidence index is applied to the largest and smallest payoffs that every player could receive once the core is determined. A confidence index near one means an optimistic player who expects to capture most of

[47] See http://mathworld.wolfram.com/BarycentricCoordinates.html

the value to be distributed in the second stage, whereas a confidence index close to zero means the opposite [157].

Recalling that the core can be non-empty or empty, we also have to deal with games that have an empty core. Summerfield & Dror [158] develop a methodology that treats a biform game as a two-stage stochastic programming problem with recourse, which deals with either empty or non-empty core games. This methodology is defined as follows:

$$f_i\left(z_i^*, z_j^*, z_k^*\right) = max_{z_i \in \{0,1\}} - c^1(z_i) + Q_i\left(z_i, z_j, z_k\right) \quad \text{(III.4)}$$

where:

$$Q_i\left(z_i, z_j, z_k\right) = max_{T \subseteq \{i,j,k\}}\ \alpha_i \overline{x_i}^{T,\left(z_i, z_j, z_k\right)} + (1 - \alpha_i)\underline{x_i}^{T,\left(z_i, z_j, z_k\right)} \quad \text{(III.5)}$$

$s.t.$

$$C(T, v) \neq \emptyset \quad \text{(III.6)}$$

Here, players $i, j, k \in I$ and $i \neq j \neq k$. Furthermore, $T \subseteq P(I)$ represents a stable subcoalition with a non-empty core (in the second stage or cooperative part of the game) that maximises player i's expected payoff. That is, a coalitional game $\Gamma = (I, v)$ will be a subgame $\Gamma = (T, v)$ with $\emptyset \neq T \subseteq P(I)$, so T can be now also be treated as a coalition. It is important to notice that all coalitional values based on T are equal to those based on I. The players' decisions in the non-cooperative part or first stage of the game are represented by $z_i \in \{0, 1\}$. The term $-c^1(z_i)$ denotes a decision cost during the first stage, derived from the second stage symbolised by $Q_i\left(z_i, z_j, z_k\right)$. $\overline{x_i}$ and $\underline{x_i}$ represent the upper and lower payments, respectively, that a particular player could receive. We consider this approach for games with an empty core.

III.3 An application of biform games to the community energy sector

III.3.1 Framework

In this section, a specific application of biform games to the community energy sector is formulated to better understand this phenomenon from an economic-strategic perspective. Bearing in mind the concepts defined above, the assumptions for this applied model are as follows.

We consider two residential electricity customers, who have the option to participate in energy production using solar photovoltaic (PV) technology in one of two ways. The first way to do so is through a net billing distributed generation scheme, jointly carried out with a distributor or supplier as is usual in several countries, including Chile and the UK, in which customers can individually buy (rooftop) solar PV panels. A net billing scheme can be technically defined as a scheme where the energy injection is valued at an injection rate that is different from the consumption rate. The resulting value is then subtracted from the energy consumption expenses [133]. The other way is having an agreement only between both residential electricity customers to build and set up a small-scale solar PV power plant, which is conceived to satisfy their electricity consumption. If the residential electricity customers decide not to participate in energy production, they can maintain a regular electricity provision scheme from a distributor or supplier. We assume that, all players perfectly know the costs, tariffs, rights, and obligations derived from their relations with other players in all three cases.

We model the aforementioned situation as three-player (coalitional) games with transferable utility. The cooperation agreements are negotiated by the players and can be enforced by some outside party, if necessary. The games can then be defined as follows:

$$\Gamma = (I, v) \tag{III.7}$$

where:

$\Gamma =$ a three-player (coalitional) cooperative game.

$I = \{1,2,3\}$ = the players set or grand coalition.

v = a function $P(I) \rightarrow \mathbb{R}$, with $v(\emptyset) = 0$, which indicates the maximal aggregate payoff of a coalition $S \in P(I)$.

$P(I)$ = set of coalitions (i.e., the set of all subsets of I).

Additionally, I, $\emptyset$, and the single player sets $\{i\}$ (with $i \in I$), are treated as coalitions. Any payoff vector for n players is denoted as $x = (x_1, x_2 \ldots x_n) \in \mathbb{R}^n$.

We examine the three scenarios, each considering three players, for each country, as noted below in Table III.1.

Table III.1. Details of scenarios developed in each country

Relation / Scenario	Base scenario	Distributed generation scenario	Community energy scenario
Players involved	Player 1 & Player 3 Player 2 & Player 3	Player 1 & Player 3 Player 2 & Player 3	Player 1 & Player 2
Type of relation or agreement	Utility contract	Net billing scheme	Project through a legal organisation for self-consumption
Coalitions	$\{1,3\}, \{2,3\}$	$\{1,2,3\}$	$\{1,2\}$

III.3.2 Key definitions and assumptions for payments and coalitional values

To determine the payments for each player and the corresponding coalitional values[48], we formulate the following equations:

a) Annual customers' electricity consumption payments at present value, $APPV_C$.

$$APPV_C = [(Dt_C \times AAC_C)/r][1 - 1/(1+r)^t] \qquad \text{(USD/year)} \qquad \text{(III.8)}$$

[48] The exchange rates considered for all calculations are USD/CLP 619.6 and USD/GBP 0.758 according to OANDA.com.

b) Annual distributor's/supplier's requirements payments at present value, $APPV_D$.

$$APPV_D = APPV_C\ (1 - \omega) \quad \text{(USD/year)} \qquad \text{(III.9)}$$

c) Annual generation payment obtained by customers at present value, $AGPV_C$.

$$AGPV_C = [(GT_C \times AAG_C)/r][1 - 1/(1+r)^t] \quad \text{(USD/year)} \qquad \text{(III.10)}$$

where:

Dt_C= Distribution or supply tariff paid by customers.
AAC_C= Customers' annual average consumption.
GT_C = Generation tariff received by customers.
AAG_C = Customers' annual average generation.
ω = Added value generated and captured by the distributor/supplier, between 0 and 1.
r = Discount rate.
t = Period of time, in years.

Regarding the parameter Dt_C, we take into consideration representative tariffs from one of the main distributors/suppliers in each country, as shown in Table III.2.

Table III.2. Representative electricity tariffs assigned to customers in Chile[49] and Scotland[50]

Data / Country	Chile	Scotland	Unit
Chilean Tariff	90.71		CLP/kWh
British Tariff		14.03	p/kWh
Tariffs in USD	0.15	0.19	USD/kWh

Sources: [196,197]

[49] Valid at September 2017, considering the BT1 tariff including energy, capacity buying, distribution capacity, pool coordination and transmission use.
[50] Valid at September 2017, considering a simple average of all locations of British Gas Standard domestic single rate electricity for Direct Debit payment, with effect from 15-09-2017.

The term AAC_C is defined according to the following criteria:

a) For player 1, we assume this player consumes 1,800 kWh/year in Chile [115] and 3,505 kWh/year in the UK [198], as we recognise this player as a residential low-middle income consumer of electricity.
b) For player 2, we assume this player consumes 7,865 kWh/year in Chile [115] and 4,972 kWh/year in the UK [198], as we recognise this player as a residential high income consumer of electricity.
c) It is important to notice that player 3 is a distributor (in Chile) or supplier (in Scotland) of electricity.

Concerning the term GT_C, we consider that players 1 and 2 have access to a sale (generation) rate of 0.10 USD/kWh [197] and 0.05 USD/kWh [199] in Chile and Scotland, respectively.

We parameterise AAG_C considering information about the potential generation of solar PV panels in Chile and Scotland. For the Scottish case, we take data from the Energy Saving Trust's Solar Energy Calculator considering as the consumer's location the city of Edinburgh, a roof slope of 45°, a shading less than 20% of the sky, with a southeast direction of the roof, and a medium installation size. The potential generation derived from the use of solar PV panels and corresponding costs are shown in Table III.3.

Table III.3. Potential generation derived from solar PV panels use and the related costs in Chile and Scotland

Criteria / Country	Chile	Scotland
Main location	Santiago	Edinburgh
Installed capacity	2 kWp	2 kWp
Potential annual generation	3,000 kWh	1,520 kWh
Cost (Local currency)	CLP 3,390,000	GBP 4,000
Solar PV Cost (USD)	5,471.27	5,277.05

Sources: [122,200]

In order to determine the overnight capital cost $OCC_{per\ household}$, and then estimate the cost per household of a solar PV power plant in a community energy project which meets the capital requirements, we consider an $OCC_{per\ household}$ of 2,020 USD/kW and a capacity factor of 0.2 [201]. Moreover, we take the number of residential electricity customers of one municipality/council in each country, where we can find similar features for both residential customers. The selected places are Lo Barnechea for Chile, and The City of Edinburgh Council for Scotland, which have 364,868 customers [202] and 241,433 customers [203], respectively. In the Scottish case, it is important to note that we assume that each separate dwelling is a separate residential electricity customer. Furthermore, for practical purposes, and because it would be unrealistic to think that everyone could participate in this kind of initiative at the same time in a certain place, we just take a small proportion of those customers (0.1%) as potential participants. We assume that a half of them are low-middle income customers (player 1) and the rest are high income customers (player 2). The calculation details related to $OCC_{per\ household}$ for each country, are summarized in Table III.4.

Table III.4. Overnight Capital Cost (OCC) per household

Item / Specific Location	Lo Barnechea Municipality	City of Edinburgh Council	Unit
Selected customers	365	241	
Customers as player 1	182	121	
Customers as player 2	182	121	
Consumption player 1	328,381	423,111	kWh/yr
Consumption player 2	1,434,843	600,202	kWh/yr
Required capacity player 1	187	242	kW
Required capacity player 2	819	343	kW
Total required capacity	1,006	584	kW
OCC player 1	378,613	487,834	USD
OCC player 2	1,654,329	692,014	USD
$OCC_{per\ household}$ player 1	2,075	4,041	USD
$OCC_{per\ household}$ player 2	9,068	5,733	USD

The term ω is quantified by considering information from distributor's financial statements from 2012 to 2016, in order to have a representative measure of the value generated and captured by player 3, after receiving payments from players 1 and 2, and paying player 3's suppliers. We set ω to the average operating margin, defined as operating profit divided by revenues due to the core activities; 13% [204] and 5% [205] for the Chilean and Scottish case, respectively.

We use a discount rate r =10% and consider a 25-year horizon, which is the approximate useful life of solar PV panels [121]. Using these parameters, we bring all financial payments to their present value assuming a uniform time horizon.

Considering equations (III.8) to (III.10) and all the information shown above, the payments for each player are based given by the following equations:

Table III.5. Formulas to compute the payments for each player in every scenario

	Base scenario	Distributed generation scenario	Community energy scenario
Player 1	$(\text{III}.8)$	$(\text{III}.10) - [(\text{III}.8) + \text{Solar PV Cost}]$	$(\text{III}.8) - OCC_{per\ household}$
Player 2	$(\text{III}.8)$	$(\text{III}.10) - [(\text{III}.8) + \text{Solar PV Cost}]$	$(\text{III}.8) - OCC_{per\ household}$
Player 3	$(\text{III}.8) - (\text{III}.9)$	Chilean case: $[(\text{III}.8) - (\text{III}.10) + \text{Solar PV Cost}] - \{[((\text{III}.8) - (\text{III}.10)) \times (1-\omega)] + [(\text{Solar PV Cost}) \times (\text{1-30\%})]\}$ Scottish case: $[(\text{III}.8) - (\text{III}.10)] - \{[((\text{III}.8) - (\text{III}.10)) \times (1-\omega)]\}$	0

Table III.5. lists the nature of all payments for each player, under the three scenarios described above. Accordingly, the payments under the base scenario represent how much players 1 and 2 pay for their electricity consumption to the distributor or supplier, which is simultaneously the amount that the latter receives, minus the corresponding costs based on the specified profit. The payments under the distributed generation scenario represent how much players 1 and 2 receive for the energy production from their solar PV panels, minus their electricity consumption and solar PV panel investment costs. At the same time, player 3 receives payments for the residential customers' consumption, minus their solar PV generation, and the corresponding costs based on a specific margin. It is worth nothing that, in Chile, players 1 and 2 can buy solar PV panels from distribution companies (we assume that the distributor's profit margin on solar panel sales is 30%) and specialised vendors, unlike in Scotland, where customers can only buy them from specialized vendors[51]. These differences are reflected in the corresponding formulas. The payments for the community energy scenario imply that players 1 and 2 receive the savings derived from their reduction in electricity consumption payments to the supplier or, alternatively,

[51] The cost of solar PV panels is taken as an average of the values listed in http://www.theecoexperts.co.uk/how-much-do-solar-panels-cost-uk#/3 for devices of 2 kWp of installed capacity.

that the community-led project receives electricity payments, minus a lump-sum cost per player or household which represents their share in the project.

Assuming that the costs of solar PV panels and OCC are covered in just one instalment, we calculate the payments for each player, scenario, and country, taking into account all equations from Table III.5., as shown in Tables III.6. and III.7.

Table III.6. Payments received by every player and scenario in the Chilean case (amounts in USD)

Payments per player / Scenarios			Base scenario	Distributed generation scenario	Community energy scenario
Positive payments	Players	1	-	2,723.11	2,450.80
		2	-	2,723.11	10,708.64
		3	13,159.44	18,655.75	-
Negative payments	Players	1	-2,450.80	-7,922.07	-2,075.34
		2	-10,708.64	-16,179.91	-9,068.09
		3	-11,448.71	-14,370.27	-
Final payments	Players	1	-	-	375.46
		2	-	-	1,640.54
		3	1,710.73	4,285.48	-

Table III.7. Payments received by every player and scenario in the Scottish case (amounts in USD)

Payments per player / Scenarios			Base scenario	Distributed generation scenario	Community energy scenario
Positive payments	Players	1	-	689.86	6,044.85
		2	-	689.86	8,574.90
		3	14,619.75	13,240.04	-
Negative payments	Players	1	-6,044.85	-11,321.90	-4,041.15
		2	-8,574.90	-13,851.94	-5,732.56
		3	-13,888.77	-12,578.04	-
Final payments	Players	1	-	-	2,003.70
		2	-	-	2,842.34
		3	730.99	662.00	-

Because the core is considered within the concept of biform games, we clip all negative payments to zero. We therefore define all coalitions and their values, considering the data shown in Tables III.6. and III.7., in order to compute and solve the games presented in Tables III.8. and III.9., as shown below.

Table III.8. Game 1 - Coalitions and their values for each scenario in the Chilean case (amounts in thousands of USD, which come from Table III.6.)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1,2\}$				2.02
$\{1,3\}$		0.32		
$\{2,3\}$		1.39		
$\{1,2,3\}$			4.29	

Table III.9. Game 2 - Coalitions and their values for each scenario in the Scottish case (amounts in thousands of USD, which come from Table III.7.)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1,2\}$				4.85
$\{1,3\}$		0.30		
$\{2,3\}$		0.43		
$\{1,2,3\}$			0.66	

In these two tables, the sum of the values associated to coalitions $\{1,3\}$ and $\{2,3\}$ are equal to the final payment for player 3 in the base scenario in Tables 6 and 7. There are two terms in that sum, which correspond to player 1's and player 2's value under coalition with player 3 separately, according to the nature of the base scenario.

As a sensitivity analysis, we now modify the values in Tables III.8. and III.9. to clearly see the effects of cost subsidisation on the confidence indexes and Nash equilibria. For simplicity, we consider a support scheme in which solar PV panel costs and OCC are covered by annualised payments, mostly made by a subsidising entity, such as a government. Specifically, we consider a case in which consumers make only one payment in the first year of the project, after which the government pays the rest[52]. This implies

[52] Alternatively, once could find an equivalent investment cost subsidy that would give the same solution; for simplicity, we do not consider this.

that the payments series occur during the solar PV panels useful life mentioned before. In relation to the distributed generation scenario, we also now consider that solar PV panels are bought from specialised vendors in both countries. This means that, for the Chilean case, consumers can buy solar PV panels at a 50% lower cost.

The games and their corresponding coalitional values for this sensitivity analysis are shown in Tables III.10. and III.11.

Table III.10. Game 3 - Coalitions and their values for each scenario in the Chilean case (amounts in thousands of USD)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1, 2\}$				11.93
$\{1, 3\}$		0.32		
$\{2, 3\}$		1.39		
$\{1, 2, 3\}$			1.00	

Table III.11. Game 4 - Coalitions and their values for each scenario in the Scottish case (amounts in thousands of USD)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1, 2\}$				13.54
$\{1, 3\}$		0.30		
$\{2, 3\}$		0.43		
$\{1, 2, 3\}$			0.66	

In Tables III.10. and III.11., as before, the sum of the values associated to coalitions $\{1, 3\}$ and $\{2, 3\}$ are equal to the final payment for player 3 in the base scenario.

III.3.3 Procedural considerations

In all these three-player games there are two components of decisions: a non-cooperative and a cooperative one. The non-cooperative component represents an individual decision to get involved in an electricity generation project or simply buy electricity through a standard supply agreement. The cooperative component represents the possible payoffs and their distribution among the players who have decided to become involved in energy production. This involves negotiation power implications, as mentioned before. Consequently, given that we need to calculate the core to solve the cooperative part of each game, we consider a triangle with barycentric coordinates, following the next inequality:

$$v(\{i,j,k\}) - x_k \geq v(\{i,j\}) \tag{III.11}$$

$$x_k \leq v(\{i,j,k\}) - v(\{i,j\}) \tag{III.12}$$

With $i \neq j \neq k$ and $i,j,k \in I$

Then:

$$\begin{aligned} C(v) = \{x_i, x_j, x_k \in \mathbb{R}^3 : x_i + x_j + x_k = v(\{i,j,k\}), v(\{i\}) \leq x_i \\ \leq v(\{i,j,k\}) - v(\{j,k\}), v(\{j\}) \leq x_j \leq v(\{i,j,k\}) - v(\{i,k\}), \\ v(\{k\}) \leq x_k \leq v(\{i,j,k\}) - v(\{i,j\})\} \end{aligned} \tag{III.13}$$

Apart from the considerations related to the calculation of the core, it is important to verify whether the core is non-empty or empty. To do so, we take into account the following inequalities which have to be met at the same time, according to the Bondareva-Shapley theorem [192-195]:

For superadditivity:

$$v(\{1\}) + v(\{2\}) \leq v(\{1,2\}) \tag{III.14}$$

$$v(\{1\}) + v(\{3\}) \leq v(\{1,3\}) \tag{III.15}$$

$$v(\{2\}) + v(\{3\}) \leq v(\{2,3\}) \tag{III.16}$$

$$v(\{1\}) + v(\{2,3\}) \leq v(\{1,2,3\}) \tag{III.17}$$

$$v(\{2\}) + v(\{1,3\}) \leq v(\{1,2,3\}) \tag{III.18}$$

$$v(\{3\}) + v(\{1,2\}) \leq v(\{1,2,3\}) \tag{III.19}$$

For convexity:

$$v(\{1,2\}) + v(\{1,3\}) \leq v(\{1,2,3\}) + v(\{1\}) \tag{III.20}$$

$$v(\{1,2\}) + v(\{2,3\}) \leq v(\{1,2,3\}) + v(\{2\}) \tag{III.21}$$

$$v(\{1,3\}) + v(\{2,3\}) \leq v(\{1,2,3\}) + v(\{3\}) \tag{III.22}$$

For balancedness:

$$v(\{1,2\}) + v(\{1,3\}) + v(\{2,3\}) \leq 2v(\{1,2,3\}) \tag{III.23}$$

In games with an empty core, Summerfield & Dror's [158] approach is considered as described above. Recalling that the players' decisions in the first stage of the game are represented by $z_i \in \{0, 1\}$, we assume for simplicity that the decision cost during the first stage is $-c^1(z_i) = 0$; this could easily be generalised to include first-stage decision costs. In terms of the upper and lower payments $\overline{x_i}$ and $\underline{x_i}$, since $\overline{x_i}$ and $\underline{x_i} \in \mathbb{R}^n$ and we assume transferable utility games, then $\alpha_i \overline{x_i} + (1 - \alpha_i)\underline{x_i} = x_i$. This implies that $\overline{x_i}$ and $\underline{x_i}$ represent player i's income and costs, respectively, which form the coalitional values listed above. Accordingly, player i is confident about the influence that incomes or expenses might have on the final payoff. This will allow determining the upper and lower bounds that are necessary to use the confidence indexes, even when there is an empty core and the grand coalition may form. Considering this, we solve (III.4), (III.5), and (III.6).

Another aspect is that, in reality, players might not have perfect information about each other's confidence indexes; hence, they might not know which coalitions the other players prefer. We therefore propose an alternative approach that combines the benefit of using probability distributions and the idea behind the confidence index. In this approach, we assume that each confidence index (α_i) follows a uniform distribution. This implies that each degree of confidence about the final payoff has the same probability, because none of the players knows anything about other players' confidence. We determine the Nash equilibrium (best strategy, coalition, and final payoff) for each player, randomly sampling 10,000 points from each distribution by solving (III.4), (III.5) and (III.6). This will help to better understand which project (coalition) prevails when players do not know the other players' confidence indexes. Furthermore, this will give an idea about the likelihood of coalition formation. To track the final results, we model a matrix that is shown in Fig. III.2. In this matrix, player 1 chooses the rows, player 2 chooses the columns, and player 3 chooses the matrices.

	$z_3 = 0$						$z_3 = 1$					
	$\{\emptyset\}$ $z_2 = 0$			$\{2\}$ $z_2 = 1$			$\{3\}$ $z_2 = 0$			$\{2,3\}$ $z_2 = 1$		
$z_1 = 0$	0	0	0	0	0	0	0	0	0	0	x_i	x_i
$z_1 = 1$	0	0	0	x_i	x_i	0	x_i	0	x_i	x_i	x_i	x_i
	$\{1\}$			$\{1,2\}$			$\{1,3\}$			$\{1,2,3\}$		

Fig. III.2. Matrix for tracking best strategies / coalitions

III.4 Results

We first verify whether our games have a non-empty core, by computing inequalities (III.14) to (III.23). The findings of this procedure are shown in Table III.12.

Table III.12. Test results for Superadditivity, Convexity, and Balancedness for every game

Games / Criterion	Superadditivity	Convexity	Balancedness	Type of Core
Game 1 – Chilean case	Yes	Yes	Yes	Non-empty
Game 2 – Scottish case	Yes	No	No	Empty
Game 3 – Chilean case with cost subsidisation	Yes	No	No	Empty
Game 4 – Scottish case with cost subsidisation	Yes	No	No	Empty

As can be seen above, only game 1 has a non-empty core. We follow Branderburger & Stuart's [157] method to solve this game. For the rest of the games, we follow Summerfield & Dror's [158] approach as explained above.

III.4.1 Numerical results for game 1

Taking into account (III.3) and solving (III.11) to (III.13), we determine the core for this game considering constraints (III.24) to (III.28), which are based on the coalitional values listed in Table III.8., in order to comply with the coalitional rationality criterion and efficiency principle:

$$x_1, x_2, x_3 \geq 0 \quad \text{(III.24)}$$

$$x_1 + x_2 \geq 2.02 \quad \text{(III.25)}$$

$$x_1 + x_3 \geq 0.32 \quad \text{(III.26)}$$

$$x_2 + x_3 \geq 1.39 \quad \text{(III.27)}$$

$$x_1 + x_2 + x_3 = 4.29 \quad \text{(III.28)}$$

We therefore plot a triangle with barycentric coordinates as can be seen in Fig. III.3., which shows the possible imputations that can be freely assigned to the players, which are inside the core and comply with the two aforementioned criteria.

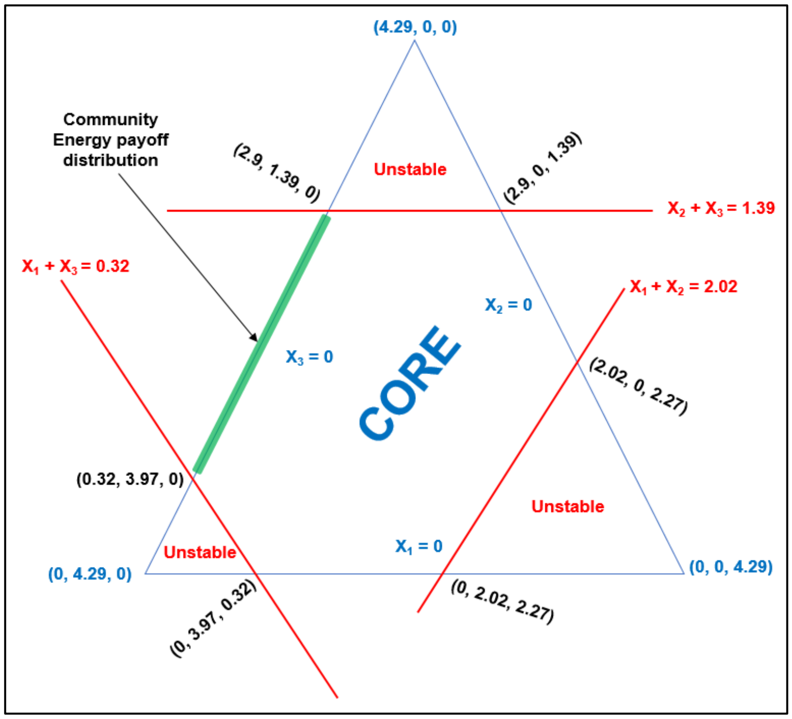

Fig. III.3. Non-empty Core for Game 1 (amounts in thousands of USD)

These results are not straightforward. If players 1 and 2 block any participation for player 3 and decide to form coalition {1,2}, the worst acceptable payoff for them will be 0.32 and 1.39, respectively. Clearly, player 3 will have the incentive to participate in another coalition, as he receives zero. In the case of being involved in another coalition, the worst acceptable payoff for players 1 and 2 will be zero. Similarly, the best acceptable payoff for players 1 and 2 will be same in either coalition {1,2} or a different one. Hence, assigning a conservative confidence index for each player, which means that each player has a neutral payoff expectation, we determine the Nash equilibrium taking the payoffs shown in Fig. III.3. and solving (III.2), as noted in Table III.13.

Table III.13. Final results for Game 1 (rounded amounts in thousands of USD taken from Fig. III.3.)

Strategies / Players	Player's possible payoffs			Player's confidence - α_i			Best strategy		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Best payoff forming {1,2}	2.9	4.0	0.0						
Worst Payoff forming {1,2}	0.3	1.4	0.0						
Best payoff forming another coalition	2.9	4.0	2.3	0.5	0.5	0.5	{1,2}	{1,2}	≠ {1,2}
Worst Payoff forming another coalition	0.0	0.0	0.3						

Forming coalition {1,2} implies that the strategy of being a consumer and/or producer of electricity by implementing a community energy project (CEP) is optimal, so we can say that the rest of the possible coalitions follow other options (No CEP). Accordingly, as can also be seen in Fig. III.4., the Nash equilibrium is (CEP), (CEP), and (No CEP) for players 1, 2, and 3, respectively.

Player 3: CEP

Player 1 \ Player 2	CEP	No CEP
CEP	1.6 2.7 0.0	1.6 2.0 0.0
No CEP	1.5 2.7 0.0	1.5 2.0 0.0

Player 3: No CEP

Player 1 \ Player 2	CEP	No CEP
CEP	**1.6 2.7 1.3**	1.6 2.0 1.3
No CEP	1.5 2.7 1.3	1.5 2.0 1.3

Fig. III.4. Nash equilibrium for Game 1 (amounts in thousands of USD)

In Fig. III.4., player 1 chooses the rows, player 2 chooses the columns, and player 3 chooses the matrices. It is important to notice that even when the confidence index changes for all players, the resulting Nash equilibrium will be the same in this case.

III.4.2 Numerical results for games 2, 3, 4, and simulation

III.4.2.1 Games 2, 3, and 4

We solve (III.4), (III.5), and (III.6), and modify each confidence index, one at a time, in order to determine the possible Nash equilibria given the specific confidence indexes. The findings are shown in Tables III.14., III.15., and III.16.

Table III.14. Game 2 - Intervals for players' confidence and corresponding Nash Equilibrium

Players' confidence	Nash Equilibrium
$0.401 \leq \alpha_1 \leq 1$ $0.401 \leq \alpha_2 \leq 1$ $0.000 \leq \alpha_3 \leq 0.487$	Community energy scenario
$0.943 \leq \alpha_1 \leq 1.000$ $0.953 \leq \alpha_2 \leq 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Distributed generation scenario
$\alpha_1 = 1.000$ $0.000 \leq \alpha_2 \leq 0.952$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {1,3}
$0.000 \leq \alpha_1 \leq 0.942$ $\alpha_2 = 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {2,3}

Table III.15. Game 3 - Intervals for players' confidence and corresponding Nash Equilibrium

Players' confidence	Nash Equilibrium
$0.086 \leq \alpha_1 \leq 1$ $0.086 \leq \alpha_2 \leq 1$ $0.000 \leq \alpha_3 \leq 0.465$	Community energy scenario
$0.503 \leq \alpha_1 \leq 1.000$ $0.802 \leq \alpha_2 \leq 1.000$ $0.466 \leq \alpha_3 \leq 1.000$	Distributed generation scenario
$\alpha_1 = 1.000$ $0.000 \leq \alpha_2 \leq 0.801$ $0.466 \leq \alpha_3 \leq 1.000$	Base scenario {1,3}
$0.000 \leq \alpha_1 \leq 0.502$ $\alpha_2 = 1.000$ $0.466 \leq \alpha_3 \leq 1.000$	Base scenario {2,3}

Table III.16. Game 4 - Intervals for players' confidence and corresponding Nash Equilibrium

Players' confidence	Nash Equilibrium
$0.069 \leq \alpha_1 \leq 1$ $0.069 \leq \alpha_2 \leq 1$ $0.000 \leq \alpha_3 \leq 0.487$	Community energy scenario
$0.906 \leq \alpha_1 \leq 1.000$ $0.930 \leq \alpha_2 \leq 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Distributed generation scenario
$\alpha_1 = 1.000$ $0.000 \leq \alpha_2 \leq 0.929$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {1,3}
$0.000 \leq \alpha_1 \leq 0.905$ $\alpha_2 = 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {2,3}

Given that coalitions {1}, {2}, {3}, and the empty coalition {∅} have the same coalitional values (equal to zero), we assume an empty solution for the first stage, namely the decisions $z_1 = z_2 = z_3 = 0$ or {∅}, if the Nash equilibrium is one of these coalitions. It is also clear that if the players' confidence indexes do not meet one of the intervals, the solution will be $z_1 = z_2 = z_3 = 0$ or {∅}.

III.4.2.2 Simulation

As explained above, we also simulate uncertainty about confidence indexes by considering 10,000 solutions to (III.4), (III.5), and (III.6), randomly and independently drawing confidence indexes from uniform distributions with support [0,1]. We then obtain the percentage of specific Nash equilibria (strategies/coalitions) out of the total number of cases/iterations, which are shown in Table III.17.

Table III.17. Nash Equilibria as a percentage out of the total number of iterations.

Strategies or coalitions / Games	Game 2	Game 3	Game 4
No relation among the players - $\{\emptyset\}$	82.74%	56.27%	56.89%
Community energy scenario	17.08%	38.63%	42.69%
Distributed generation scenario	0.18%	5.10%	0.42%

According to Table III.17., even when there is no knowledge among the players about people's confidence, there is an opportunity for implementing community energy projects in both countries, considering games 2, 3, and 4.

We also determine the minimum thresholds necessary for obtaining a particular coalition as solution, in terms of payments (x_i) and confidence indexes for each player and game. These are presented in Table III.18., and although they are naturally sensitive to the sample size, they do show that even relatively low confidence levels can be enough for a community energy project to emerge as an equilibrium solution.

Table III.18. Minimum threshold observed in 10,000 iterations, in terms of x_i and α_i (rounded amounts in USD)

Coalition	Player / Games	Game 2	Game 3	Game 4
Community energy scenario	Player 1	x_i = 2.55 α_i = 0.401 $1-\alpha_i$ = 0.599	x_i = 0.08 α_i = 0.086 $1-\alpha_i$ = 0.914	x_i = 4.6 α_i = 0.069 $1-\alpha_i$ = 0.931
	Player 2	x_i = 7.10 α_i = 0.401 $1-\alpha_i$ = 0.599	x_i = 8.57 α_i = 0.086 $1-\alpha_i$ = 0.914	x_i = 1.19 α_i = 0.069 $1-\alpha_i$ = 0.931
Distributed generation scenario	Player 1	x_i = 28.18 α_i = 0.945 $1-\alpha_i$ = 0.055	x_i = 1.59 α_i = 0.503 $1-\alpha_i$ = 0.497	x_i = 6.41 α_i = 0.907 $1-\alpha_i$ = 0.093
	Player 2	x_i = 3.75 α_i = 0.953 $1-\alpha_i$ = 0.047	x_i = 3.9 α_i = 0.802 $1-\alpha_i$ = 0.198	x_i = 7.45 α_i = 0.931 $1-\alpha_i$ = 0.069
	Player 3	x_i = 2045.93 α_i = 0.566 $1-\alpha_i$ = 0.434	x_i = 16.93 α_i = 0.466 $1-\alpha_i$ = 0.534	x_i = 58.77 α_i = 0.489 $1-\alpha_i$ = 0.511

III.5 Discussion and recommendations

III.5.1 Discussion of the games and their results

In relation to game 1 (Chilean case shown in Fig. III.3., Table III.13., and Fig. III.4.), it is important to note that this game has a non-empty core and no cost subsidisation is considered. Based on the results above, player 1 (the low-medium income residential customer) and player 2 (the high income residential customer) will form a coalition in order to carry out a community energy project, which is represented by coalition {1,2}. This strategy is the most profitable for them, under our assumptions. Player 3 (the electricity distributor) would not be interested in participating in such coalition {1,2}, as it might be offered a payment equal to zero (and then blocked to do so). If the distributor were offered a better payoff/payment, e.g., $x_3 = 1.43$ (with a core $C(v) =$

$\{x_1, x_2, x_3 \in \mathbb{R}^3: x_1 + x_2 + x_3 = 4.29,\ x_1 = 1.43,\ x_2 = 1.43,\ x_3 = 1.43\}$), such payoff distribution would not be preferred by both residential electricity customers, as there is another (better) option for them. Consequently, this would motivate blocking measures and then the community energy coalition formation, leaving the distributor aside.

In game 2 (Scottish case shown in Tables III.14., III.17., and III.18.), no costs subsidisation is considered and it has an empty core, so we adopt Summerfield & Dror's [158] solution approach. Here, the community energy coalition requires a lower income to cover the costs, as the minimum required confidence indexes to form coalition $\{1,2\}$ is relatively low ($\alpha_i \geq 0.401$). Hence, as long as both residential electricity customers have that level of confidence and the supplier is slightly pessimistic about the results of the game or negotiation process ($0 \leq \alpha_3 \leq 0.487$), the best strategy (represented by the Nash equilibrium) for all players will be the implementation of a community energy project. On the other hand, if the supplier is more confident about the results of the negotiation process ($0.487 \leq \alpha_3 \leq 1.000$) and both residential electricity customers are also more confident about the results, leaving the uncertainty aside, the best strategy will be the implementation of a net billing project. This might be also interpreted as follows: the less uncertainty (alternatively, the more confidence) you have, the more attractive the traditional electricity provision scheme is. This can be seen in all games, especially when a regular utility contract is the best strategy for all players (coalitions $\{1,3\}$ and $\{2,3\}$ in Table III.14.). Here, there is no uncertainty for both residential customers because they have to pay their bill every month, which is received by the supplier. At the same time, due to both residential electricity consumers' confidence, the supplier can participate in the coalition even when it is moderately, very, or completely confident that it can extract this revenue. The results of our probabilistic analysis also show that there are opportunities for community energy initiatives, as shown in Table III.17. The successful cases in which the best strategy for all players is the implementation of community energy projects reached 17.08%, a percentage that is higher that of distributed generation projects

(0.18%). As it happens, community energy initiatives are relatively popular in Scotland, compared to other types of citizen participation, so although our model is simple, it does go some way in explaining reality.

Considering games 3 and 4 (Chilean and Scottish case, respectively), both games present an empty core but in these cases, a cost subsidy is considered. As can be seen in Table III.15. (Chilean case), the required confidence for implementing community energy projects (represented by coalition $\{1,2\}$) reaches a very low level for both residential customers ($\alpha_i \geq 0.086$). At the same time, the distribution company may be pessimistic about the results of the game or negotiation process ($0 \leq \alpha_3 \leq 0.465$) but there would be a favourable environment for conceiving community-led projects, as the best strategy for all players is forming coalition $\{1,2\}$. The same feature can be seen in Table III.16. (Scottish case), where the required confidence for forming coalition $\{1,2\}$ is also very low for both residential consumers ($\alpha_i \geq 0.069$) and, again, the supplier may be pessimistic about how well he can perform within the bargaining process ($0 \leq \alpha_3 \leq 0.487$) but the best strategy for all incumbents will be carrying out a community energy project. In this sense, according to all possible solutions of these 2 games, including those solutions where having a regular utility contract (represented by coalitions $\{1,3\}$ and $\{2,3\}$ in Tables III.15. and III.16.) is the best strategy, we notice that the less uncertainty (alternatively, the more confidence) one has, the more traditional the electricity provision scheme is preferred. From our probabilistic results shown in Table III.17., we can see a remarkable percentage of community energy equilibria (38.63% and 42.69% for the Chilean and Scottish case, respectively), in comparison with distributed generation strategies (5.10% and 0.42% for the Chilean and Scottish case, respectively). This is not entirely surprising, as the costs of community energy have been decreased significantly.

Comparatively speaking, the confidence index for each scenario and player in games 2 and 4, which are presented in Tables III.14. and III.16. for the Scottish case, is influenced by a cost subsidisation under the community energy scenario. This effect implies a significant reduction on the required confidence index for both residential customers, in order to have a community energy initiative as solution (from $0.401 \leq \alpha_i \leq 1$ to $0.069 \leq \alpha_i \leq 1$ for both players). In relation to the distributed generation scenario, there is also a reduction in the required confidence index for the same incumbents, but by a lower amount (from $0.943 \leq \alpha_1 \leq 1$ and $0.953 \leq \alpha_2 \leq 1$ to $0.503 \leq \alpha_1 \leq 1$ and $0.802 \leq \alpha_2 \leq 1$, respectively). Although those significant reductions in the confidence indexes came from one scenario (community energy), the possible equilibria in the game were altered. This is interesting because a modification of costs structures affects the possible equilibria, and therefore the probability of a specific coalition forming. This can be noted in our simulation (shown in Table III.17.) where a cost subsidisation is considered. For example, in the Scottish case, the successful cases in which implementing community energy projects was the best strategy for all players increased from 17.08% in game 2 to 42.69% in game 4. We also notice that the likelihood of having a net billing schemes as a solution is almost zero (0.42%), which is consistent with the current market context.

III.5.2 General remarks and recommendations

Taking into account all of the above, we note some important elements. First, an appropriate payoff distribution between both residential customers can assure stability and, therefore, long-lasting coalition formation, as no attractive option would influence any change in the coalition or project. Second, the negotiation between both residential consumers will be especially crucial, given that without a successful bargaining process the emergence of the community energy project (coalition formation) might not occur. Third, the interaction between the residential customers' negotiation power and that of the distributor/supplier is critical because both residential consumers should be able to operate and run the business without any involvement from the distributor/supplier. This seems contradictory in the current context where distributors and/or suppliers play a major role in the electricity markets, especially at an end-user level. We do not want to imply that our results suggest a total exclusion of distributors, but rather suggest that they may be better placed in other supporting roles for community energy projects, such as ancillary services for small-scale projects. Thus, the regulatory environment should favour market freedom and free access to other (potential) incumbents, namely community energy projects, promoting equality in terms of negotiation and avoiding any market power exercise. Nevertheless, it is also true that promoting more flexibility and adaptability for distributors/suppliers will be necessary in case of a wider deployment of community energy projects, as this would potentially reduce their market share. Fourth, one of the most crucial assumptions we make is that residential customers can afford any level of costs, which is particularly important for games 1 and 2. This might not be true unless customers have access to a saving scheme or direct subsidies before entering the business, or simply have the money to do so. More work is needed to explore the impacts of credit constraints and policies to alleviate these. Finally, there are other factors that are not considered in this chapter; for example, the specific terms and conditions for public or private funding, how establishing PPAs or other contracts would affect the economic-strategic viability, and other expenses that might be relevant (legal, first buyer, operational, marketing, and so on). We also do not consider carbon reduction incentives. Our approach based on biform games could take these into account. For instance, PPAs, which represent a higher income for community energy initiatives, would move the conclusions towards more stability and higher economic-strategic viability for community energy initiatives. Carbon incentives would work in the same way.

Summarising, following our mild assumptions, the findings presented above support the idea that community energy projects can provide stability to their members and be economically-strategically feasible or competitive in comparison with other schemes, such as net billing distributed generation schemes. In this sense, our findings are aligned with the empirical literature studies. For instance, Walker [163] states that “local income and regeneration” is one of the key incentives for community ownership. Based on a survey, Seyfang et al. [49] notice that the economic objectives are one of the most important aspects for UK community energy groups. For a group of case studies, Hicks &

Ison [140] note that “financial benefits for shareholders and/or community” is a leading motivation. Ebers Broughel & Hampl [141] based on two large-scale representative surveys performed in Austria and Switzerland, show the existence of potential investors who are willing to invest between 1,000 and 10,000 CHF/EUR in community energy projects. Brummer [162] highlights that “economic benefits” is one of the most cited categories for a set of UK-based investigations. On the other hand, for the same set of studies notices that the most cited barrier is “lack of resources” (funding, time, and expertise). Nolden [54] shows the challenges for gathering financial resources. As noted above, the specific terms and conditions of private and/or public funding are not accounted in our approach. Berka et al. [56] notice that community energy projects face higher costs, longer project development times, and higher risks, which is influenced by six facets of an organisation or project. In our approach, none of these six facets are accounted in our approach. Abada et al. [166] establish that even when it is possible a value creation by community-led coalitions, there is no guarantee that they are viable as some members would exit the project or coalition. Again, there several factors that play a role in this case: firstly, as mentioned beforehand, this study considers a project that would be more related to our definition of distributed generation schemes. Secondly, there are also other game theory tools that are taken into account in this study. Finally, the methodology and modelling are different. As a result, we think of our approach as a complement that contributes to the existing literature and can help to get a better understanding about this phenomenon.

Based on all the aforementioned elements, some recommendations can be given:

1. Focus on community energy schemes instead of others, if a higher citizen participation in energy production is desired.
2. Evaluate the provision of long-term financial arrangements, considering the corresponding compensation or recovering mechanisms, in order to improve access to community energy projects. This may include promoting PPAs and other contracts

that can improve a project’s income generation and the recoverability of private/public funding.

3. Promote stronger collaboration among people in order to facilitate the formation of stable coalitions. In this sense, sharing/distribution rules based on biform games might be useful.
4. Define explicit public policies and goals related to the above-mentioned points, in order to have measurable and verifiable milestones of progress.

III.6 Conclusions

This chapter proposes a simple but novel approach for demonstrating the economic-strategic viability of community energy projects, which adapts biform game theory to energy markets. Given the increasing importance of the community energy sector, we see many opportunities to use biform games, which are still relatively unknown in comparison with other game theoretical tools. Using these tools will help to better understand the underlying economics of the sector.

Using publicly available real-word data, we model simple biform games for Chile and Scotland. Under mild assumptions, it is possible to see the economic-strategic viability of a wider implementation of community energy projects in both countries, as it appears to be the best strategy for residential customers. Consumer confidence is crucial, unless a significant gap between incomes and costs exists (e.g., because of subsidies), in which case the importance of that confidence is reduced. Our examples also uniformly show that the less uncertainty (alternatively, the more confidence) consumers have, the more traditional their electricity provision is likely to be.

The results shown in this work are in agreement with the current Scottish situation in community energy development, and they are useful for other countries, like Chile, that are trying to increase citizen participation in energy production. Fostering a community energy sector could be especially critical in developing countries like Chile, where this sector is still incipient while political attention is predominantly focused on other mechanisms, such as net billing. Community energy projects could contribute to the efforts to halt climate change, increasing the renewable energy participation in electricity markets, strengthening local economies, and improving the quality life of communities. Of course, there are challenges, especially in terms of affordability. However, as long as communities can be enabled to enter the business, their economic-strategic viability seems promising.

More research about the economics of the community energy emergence and more knowledge about other aspects that might be crucial to this sector are necessary, especially those matters that are not accounted in this analysis. With this chapter, we attempt to encourage further work to do so.

IV. COMMUNITY ENERGY PROJECTS IN THE CONTEXT OF GENERATION AND TRANSMISSION EXPANSION PLANNING: AN ECONOMIC APPROACH BASED ON BIFORM GAMES AND LINEAR PRODUCTION GAMES

IV.1 Introduction

The role of community energy projects in liberalised electricity markets is becoming more relevant. It is possible to see a variety of community-led projects that are currently generating energy or are being implemented in many countries around the world, with emphasis on Europe [49,55,73-75,79-81,133,160-162]. These projects which are encouraging citizen participation in (renewable) energy production and therefore helping tackle climate change and making capitalism more democratic. Such projects promise not only the provision of (clean) energy to communities, but also economic and/or social benefits, such as reduced prices of energy/electricity, employment, local income, ownership and decision-making process involvement, a more profound social cohesion, among other social initiatives [52,71,143,146,164,165].

Given their increasing significance, community energy projects can be expected to significantly influence electricity markets in the future, especially, if a genuine high citizen participation in energy production is desired. These impacts may be varied, but include changes to wholesale market prices, transmission lines investment, line congestion, investment in generation capacity, as well as cooperation and payoff distribution mechanisms among people. It is therefore crucial for incumbents in the electricity market, such as large generators, distributors or suppliers, transmission system operators, and system planners, understanding the potential effects of community energy projects, as they need to plan, manage, and deal with current and future investments or assets, current and potential customers, relations with other stakeholders, etc. Regulators and policy makers need to understand the whole-system effects derived from community energy projects to correctly quantify their benefits. Moreover, community energy project managers need to understand the interactions between their decisions and wide energy system developments.

This is challenging, as community energy initiatives are different from other investments in generation capacity. A community energy project firstly needs to assure to its members stability, in the sense of offering suitable incentives to belong to and remain in the project or coalition, and also needs to be competitive, in the sense of offering a long-term viability and attractive benefits in comparison with other projects. This illustrates the dual nature of such initiatives. On the one side, these projects need cooperation mechanisms and on the other side, need to compete against other projects. All of this needs to be addressed somehow, in order to properly evaluate the merits of community energy projects and their impact on the wider system. This might be done at the very moment of planning the expansion of the energy system, considering all the potential generation and transmission expansion investments, or when it is necessary to have an initial idea of the economic-strategic viability of such projects, before their explicit inclusion in the energy market.

Biform games [157] provide an attractive option to model projects or initiatives with the dual behaviour exhibited by community energy projects. Biform games belong to the category of hybrid games, which can tackle the cooperative and non-cooperative worlds of game theory at the same time. This methodology therefore allows a more comprehensive analysis of community energy projects as well as their economic-strategic viability. Biform games take into account the Nash equilibrium [190] and the core [206] as solution mechanisms for solving both cooperative and non-cooperatives stages within a particular game. To our best knowledge, this concept has not been widely included in generation and transmission expansion planning models, so there is a gap that deserves to be explored. We will do so in this work. Moreover, we also consider a core-based model, called linear production games [207], which will help us to address not only the economic-strategic feasibility perspective of community energy projects and their impacts on the wider energy system, but also how much new community energy capacity might be invested in, given a certain amount of resources.

Hence, in this chapter, we include biform games' and linear production games' fundamentals in a simple and intuitive bi-level generation and transmission expansion planning model. We determine the impacts of community energy projects on social welfare, nodal wholesale prices, optimal generation and transmission expansion, CO_2 emissions, as well as other forms of citizen participation in energy production. We apply this model to a simple three-node network, with two large generators, each one located at a different node. There are three groups of residential electricity customers (with different disposable incomes) located at the remaining node. These customers have the option to participate in energy production, by carrying out a community energy project or, alternatively, another energy/electricity production scheme (in this case, a distributed generation project). By solving the model, we obtain prices and investment decisions, which help better understand the economic-strategic viability and competitiveness of community energy projects in the context of a generation and transmission expansion planning process, as well as the impacts derived from their interaction with other market incumbents and/or projects, namely large generators, a transmission operator, and a system planner. The interactions among the different groups of residential electricity customers are addressed as well.

The rest of this chapter is organised as follows. In section IV.2, we present the theoretical background necessary to build up the proposed model. In section IV.3, we outline the main features and assumptions of our model. In section IV.4, the results are presented. In section IV.5, a discussion regarding those results and some recommendations is presented. Finally, section IV.6 concludes the chapter.

IV.2 Theoretical background

IV.2.1 Optimisation and equilibrium problems: an overview

Energy and electricity markets have significantly evolved during the recent decades due to several factors, such as a technological progress, better knowledge of the economic drivers behind markets, more experience and knowledge in managing electrical equipment, empowered electricity customers and their needs, permanent changes in regulation and legislation, an increase in market participants, etc. As a consequence, modelling the full complexity of energy and electricity markets has become crucial to strengthen them and better understand the interactions among the incumbents, such as large generators and retailers, retailers and residential customers, regulators and suppliers or retailers, system operators and the whole market, as well as the derived consequences and/or impacts.

Most of these models have their origins in the power systems optimisation. Optimisation models provide an intuitive, flexible, and relatively complete way to deal with many issues or situations that deserve attention. Long-term power systems optimisation models can be roughly categorised in three groups: generation expansion models, transmission expansion models, and integrated generation and transmission expansion models [208]. In these models, the objective is chiefly to minimise (maximise) costs (benefit or welfare) subject to a variety of constraints related to demand satisfaction, generation limits, budget constraints, power balance at each node, power flow constraints, security constraints, among others [208]. These models require a significant amount of data about current and future prices, interest rates, demand structures or loads, emissions, taxes, technical capacity of power units and lines, etc. These parameters are often fundamentally uncertain, which is why many models consider uncertainty and risk. [209].

In general, optimisation models can be categorised in different ways. For instance, Dagoumas et al. [210] classify models in optimisation models (with simple and multiple objective function), computable general or partial equilibrium models, and alternative models. In the same vein, Lumbreras & Ramos [211] classify the optimisation models used in generation expansion problems as classical (linear and non-linear programming problems) and non-classical (meta-heuristic algorithms that iteratively improve a solution). Of course, simple optimisation models within the above-mentioned classifications cannot easily account for strategic interactions between market participants. Gabriel et al. [212], based on the mathematical characterisation of energy markets, notice that mathematical problems with equilibrium constraints (MPEC), equilibrium problems with equilibrium constraints (EPEC), mixed complementarity problems (MCP), and variational inequality (VI), which draw on game theory to account for these interactions, are particularly useful to work on modern energy markets. These models are now increasingly being used. For instance, Hobbs & Nelson [213] present and analyse a Stackelberg-based bi-level optimisation problem which is used to quantify how customers react to subsidies and some distortions based on decisions and prices. Chao & Peck [214] present a mechanism for establishing a competitive market for transmission services, mainly based on Coasian and Pigouvian principles and the Kirchhoff's law, and therefore deploying tradable transmission capacity rights. Using a variational inequality approach, Jing-Yuan & Smeers [215] find the Nash equilibrium for an oligopolistic market with scattered generators and customers considering regulated transmission prices. Hobbs [216] develops two models "a la" Cournot, formulated as mixed linear complementarity problems, highlighting the effects on prices, welfare, profit, among others, considering arbitrage and perfect competition as well. Pineau & Murto [217] address the uncertainty on investments decisions by modelling an optimisation problem for players who might devote money in new thermal capacity, using variational inequality and mixed complementarity problem approaches. Sauma & Oren [218] formulate MPEC and EPEC problems in order to evaluate the impacts on social welfare and location of transmission investments, taking into account the generators' expansion response to transmission expansion and congestion protocols. Later, the same authors [219] extend the concept of proactive transmission planning stated in [218] to show the impacts of different planning objectives on network optimal expansions. Ruiz & Conejo [220] reveals a procedure to obtain an optimal offering strategy for a strategic power producer based on the development and solution of an MPEC. Pozo et al. [221] propose a mixed integer linear programming optimisation problem which integrates transmission and generation investment planning, as well as market operation decisions, and characterises the pure Nash equilibria related to generation expansion (EPEC) as a set of linear inequalities. Lo Prete & Hobbs [167] develop a cooperative game theoretic approach, considering optimisation models for market agents coalitions, and note the impacts on prices, costs, and benefits derived from the introduction of a microgrid in a regulated network. Munoz et al. [222] examine the impacts derived from risk aversion on generation and transmission investments by modelling a proactive risk-averse transmission planner problem (Stackelberg equilibrium problem). More recently, Acuña et al. [223] establish a Stackelberg game considering generators and intermediaries (marketers), which is implemented throughout a bi-level optimisation problem, in order to evaluate two cooperation schemes between them.

However, none of these models is appropriate for the analysis of community energy projects, as they are all based on non-cooperative game theory and therefore cannot properly consider the dual cooperative and non-cooperative nature of community energy initiatives. Biform games theory offers an alternative which, to our best knowledge, has not been applied to generation and transmission expansion planning models that focus on community energy promotion and deployment.

IV.2.2 State-of-art community energy planning optimisation models

Optimisation problems applied to community energy matters have recently attracted some attention. For example, Huang et al. [224] survey some of the available tools, identifying a variety that would be useful for community energy promotion and deployment. Ashok, based on an optimisation model, finds that micro-hydro-wind systems are the optimal solution to electrify rural villages in India [225]. Cai et al. [226,227] develop a method based on different optimisation techniques and show different community-scale renewable energy alternatives for a study system comprised of three typical communities. Mendes et al. [228] highlight and recommend appropriate optimisation planning models/tools for integrated community energy systems (ICES), noting that a Distributed Energy Resources Customer Adoption Mode (DERCAM) might be a good tool for designing ICES given its three-level optimisation algorithm. Moret & Pinson [229], based on optimisation models and communication-based fairness indicators, study the interaction between an energy collective (formed by a community manager, a prosumer, and energy production assets) and the market and system operator and/or other energy collectives. Roy & Ni [230] develop a game theoretic approach for a distributed power system (distributed operators and residential customers) and highlight that residential consumption is relevant to control prices as well as consumers. They not only find the market clearing price at the Nash equilibrium point, but also show that residential customers individually reduce costs. Olivella-Rosell et al. [231] propose a novel optimisation problem for managing flexible energy resources throughout a Smart Energy Service Provider (SESP), considering (residential) prosumers and energy cooperatives. Yazdanie et al. [232] study decentralised generation and storage benefits for rural places in Switzerland by developing and solving a least-cost optimisation model and scenarios, and note that small hydro and solar PV improve self-sufficiency, storage improves results, and carbon pricing mitigates pollutant emissions.

The aforementioned investigations show the contributions that mathematical programming can provide to community energy matters. However, they are often unclear about what community energy really means and what the differences are with other concepts such as microgrids or distributed generation projects. They also do not consider the hybrid nature (cooperative and non-cooperative) of community energy initiatives. For this reason, in the next section we provide our definition of community energy and distributed generation projects, which we will use to define our own modelling approach.

IV.2.3 Key definitions

In order to develop our approach, based on biform games, to generation and transmission expansion planning modelling, it is important to first define the concepts of community energy and distributed generation. Regarding the former concept, its fundamentals can be found in [35,36]. There are also other studies that take these fundamentals and add more elements that contribute to an updated definition, which can be seen for example in [49,71,133,161]. We consider the updated definition of community energy based on the Scottish experience proposed in [133]. Hence, a community energy project, in our context, is "a project conceived, carried out, and implemented by people who are interested in generating energy, located in or close to the project, well-organised under a legal and organisational structure, the owner or have control of the project ownership, the main beneficiary, and interested in welfare maximisation as well as income generation". On the other side, in relation to the distributed generation concept, we take into consideration the definition stated by Ackermann et al. [31], in which a distributed generation project is defined as "an electric power source connected directly to the distribution network or on the customer site of the meter". Within this concept, it is possible to find specific citizen-oriented electricity provision schemes, such as net billing or net metering schemes. In this work, the former is considered. Therefore a net billing scheme (or distributed generation scheme for the purposes of this work) can be simply defined as a scheme where the energy injection is valued at a rate that is different from the consumption rate, and the resulting value is therefore subtracted from the energy consumption expenses. We reflect this situation in this work by establishing a case where residential customers have an opportunity to install mainly residential rooftop solar photovoltaics (PV) panels for self-consumption and selling/injecting any disposable surplus to the grid. This case is equivalent to the current Chilean net-billing scheme [133].

Having defined these concepts, we will develop a generation and transmission expansion planning process model that can include both community energy and distributed generation projects. Since an understanding of biform games is fundamental to the rest of this chapter, we first set out their main characteristics in the next section.

IV.2.4 Biform games main aspects

Game theory considers a set of rational decision-makers (or players) who determine the best possible result, as well as the corresponding strategy for obtaining it. Consequently, games can be cooperative (where players cooperate), non-cooperative (where players do not cooperative), and hybrid. Biform games theory is part of the wider game theory field, and specifically deals with hybrid games that include cooperative and non-cooperative stages.

Following Brandenburger & Stuart [157], a biform game can formally be defined as follows:

$$(Z_i, \ldots, Z_n; V; \alpha_i, \ldots, \alpha_n) \tag{IV.1}$$

where:

Z_i is a finite strategy set for each $i = 1, \ldots, n$ player.
z_i is the player i's selected strategy.
V is a map from $Z_i \times \ldots \times Z_n$ to the set of maps $P(I) \to \mathrm{I}R$, with $V(z_i, \ldots, z_n)(\emptyset) = 0$ for every $z_i, \ldots, z_n \in Z_i \times \ldots \times Z_n$.
α_i is the player i's confidence index, which is between 0 and 1.

The set of strategies $z_i, \ldots, z_n \in Z_i \times \ldots \times Z_n$ defines a transferable utility game with characteristic function $V(z_i, \ldots, z_n): P(I) \rightarrow \mathrm{I}R$, where $P(I)$ is the set of all subsets of the players set I. As a result, for each coalition $S \subseteq I$, $V(z_i, \ldots, z_n), (S)$ is the value created by coalition S, given that the players choose the strategies $z_i, \ldots, z_n$. Consequently, the steps shown below need to be followed to solve a biform game [157]:

1. Determine the core for the cooperative part or second stage of the (biform) game.
2. Calculate the range of payoffs for each player.
3. Use α_i and (1-α_i) to compute the weighted average in order to evaluate the cooperative part of the game, applying that index to the largest and smallest payoffs that every player could receive.
4. Assign to player i a payoff equal to the i's weighted average, in order to reduce the cooperative stage to a non-cooperative game.
5. Compute the Nash equilibrium of the non-cooperative part or first stage of the game.

Here, we notice that there are two solution mechanisms considered when solving biform games, one for the cooperative (second) stage and another for the non-cooperative (first) stage, namely the core and Nash equilibrium, respectively.

Regarding the core [192,193,206], this solution mechanism can be defined as follows:

$$C(v) = \{x \in \mathrm{I}R^n | \sum_{i \in I} x_i = v(I), \sum_{i \in S} x_i \geq v(S) \ \forall \ S \in P(I)\} \quad \text{(IV.2)}$$

The core is then a mathematical way to distribute payoffs among the players within a cooperative game, where $\sum_{i \in I} x_i$, which represents the sum of all players' payoffs that belong to the players set I (or grand coalition), has to be equal to $v(I)$, which represents the coalitional value of I, in order to comply with a condition called the efficiency principle. At the same time, $\sum_{i \in S} x_i$, which represents all players' payoffs that belong to a certain coalition S, has to be greater than or equal to $v(S)$, which represents the coalitional value of S, in order to comply with another condition called coalitional rationality. Thus, as long as a payoff distribution complies with these two conditions, i.e. the payoff distribution is within the core, no player will have an incentive to unilaterally leave (change) the coalition. However, it is important to note that the core might be either non-empty (implying a feasible solution) or empty (implying an unfeasible solution). To assure that a game has a non-empty core, it has to be balanced according to the Bondareva-Shapley theorem [194,195]. The Bondareva-Shapley theorem can be explained as follows: a family $S_1, S_2, \ldots, S_m$ of subsets of I is balanced over I if positive numbers or weights $w_1, w_2, \ldots, w_m$ exist, such that $\forall \ i = 1,2, \ldots, n$ the following equality holds:

$$\sum_{j:i \in S_j} w_j = 1 \tag{IV.3}$$

Similarly, a cooperative game $\Gamma = (I, v)$ is balanced if for any balanced family $S_1, S_2, \ldots, S_m$ over I, with weights $w_1, w_2, \ldots, w_m$, the following inequality holds:

$$\sum_{j=1}^{m} w_j v(S_1) \leq v(I) \tag{IV.4}$$

Therefore a game $\Gamma = (I, v)$ has a non-empty core if and only if $\Gamma = (I, v)$ is a balanced game.

Regarding the Nash equilibrium [190], this solution mechanism can be defined as follows:

The strategies $z_i^*, \ldots, z_n^*$ are a Nash equilibrium if z_i^* is the player i's best response to the other players' strategies $z_1^*, \ldots, z_{i-1}^*, z_{i+1}^*, \ldots, z_n^*$ that solve the following optimisation problem:

$$Max_{z_i \in Z_i} f_i(z_1^*, \ldots, z_{i-1}^*, z_i^*, z_{i+1}^*, \ldots, z_n^*) \tag{IV.5}$$

The payoff function f_i is based on the cooperative part of the biform game, which can be solved by the core.

Another relevant feature of biform games is that they take into account a confidence index, which is the link between the cooperative stage and the non-cooperative part of the game. This index can be interpreted as the players' expectation about the outcome of the game, in terms of how well they could do within the game and therefore how much of the total coalitional value they could capture. This index is related to perceived competition and negotiation opportunities among the players [157].

In terms of specific applications of biform games, it is possible to find several studies with applications to microeconomics, particularly, the newsvendor problem [180], monopoly and market power [181], competitive advantages of intermediaries [182]; to management matters, namely manufacturing and supply chain [183,184,187], investment in relationship support assets [186], innovation networks [188], strategic mental models [189]; and even to telecommunications [185]. There is no specific application of biform games to generation and transmission expansion planning optimisation problems, even without considering community energy projects. Thus, in our opinion, given the expanding role of community-led energy projects in electricity markets, there is a need to develop biform transmission and generation expansion models, as we do here.

IV.2.5 Linear production games main aspects

Before formulating the proposed model and its main features, it is important to mention another type of game that is considered in this work: the linear production game. These games can be useful in situations where there are producers that want to produce goods maximising their profit, considering market prices, subject to limited available resources (bundles). Owen [192,207,233] demonstrates that these games are balanced and therefore have a non-empty core, according to the Bondareva-Shapley theorem [194,195] shown above. These games can be mathematically formulated as follows:

$$v(S) = Max \quad p_1\, good_1 + p_2\, good_2 + \ldots + p_r\, good_r \tag{IV.6}$$

Subject to

$$R_{1_1}\, good_1 + R_{1_2}\, good_2 + \ldots + R_{1_r}\, good_r \leq \sum_{i \in S} R_{i_1}(S) \tag{IV.7}$$

$$R_{2_1}\, good_1 + R_{2_2}\, good_2 + \ldots + R_{2_r}\, good_r \leq \sum_{i \in S} R_{i_2}(S) \tag{IV.8}$$

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$$R_{q_1}\, good_1 + R_{q_2}\, good_2 + \ldots + R_{q_r}\, good_r \leq \sum_{i \in S} R_{i_q}(S) \tag{IV.9}$$

where:

$v(S)$ is the coalitional value of coalition $S \in I$.
p_r is the market price for good r.
R_{q_r} is the amount of resource q necessary to linearly produce the good r.
$\sum_{i \in S} R_{i_q}(S)$ is the sum of the amounts of resource q contributed by player i to coalition S, which player i belongs to.

As a consequence of this mathematical formulation, this type of game considers how coalition S should produce/launch any good r and maximise the corresponding profit taking into account the market price p_r for that good, subject to the amount/quantity of resource q that any player i, who belong to S, contribute to the coalition $\sum_{i \in S} R_{i_q}(S)$. This can be used to model a cooperative energy project which is financed by its members. One of the most useful properties here is that the solution of this problem is within the core, so there is no incentive for any player to unilaterally change its production level.

The use of all these elements in the proposed model is shown in the next sections, where the main features, assumptions, and mathematical representations can be found.

IV.3 Main features and assumptions of the model

IV.3.1 Framework and main data

In this section, we present the main features and assumptions of our model. First of all, our simple test network is shown in Fig. IV.1.

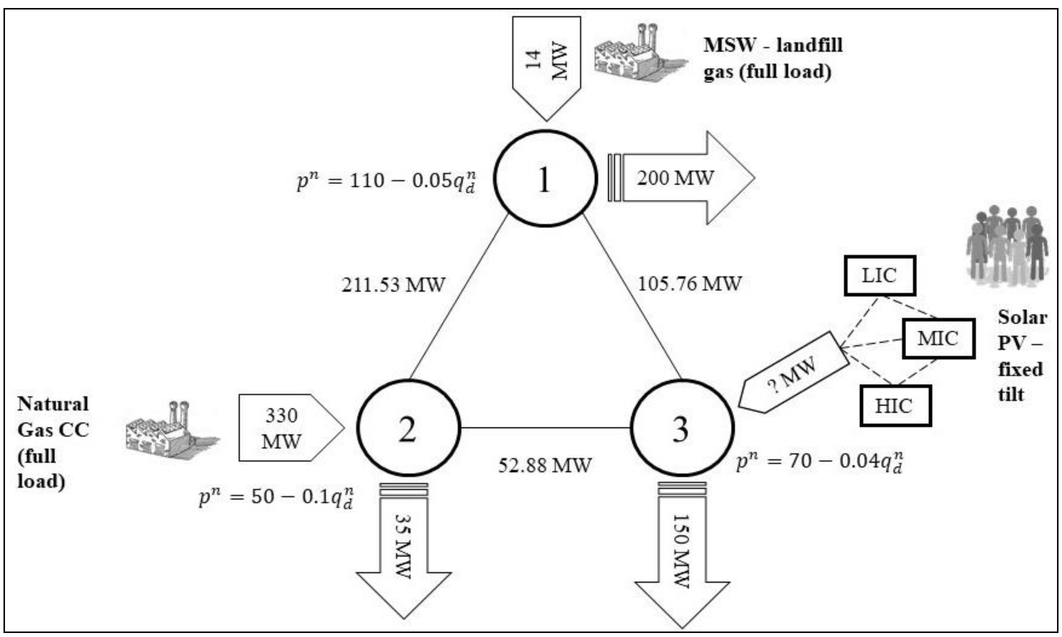

Fig. IV.1. Market representation to be examined

As it is represented in Fig. IV.1., in this market there are three nodes, which have the relatively inelastic demand function features and peak loads shown in Table IV.1.:

Table IV.1. Demand function features and peak loads at each node

Node	Intercept	Slope	Peak load (MW)
1	110	-0.05	200
2	50	-0.1	35
3	70	-0.04	150

Moreover, there are two large generators located at nodes 1 and 2, which represent a municipal solid waste/landfill gas power plant (MSWLG) and a natural gas combined cycle power plant (NGCC), respectively. Their technical and economical features are shown in Table IV.2.

Table IV.2. Technical and economical features of large generators at nodes 1 and 2

Node	Generation costs (USD/MWh)	Generation investment costs (USD/MW)	Maximum capacity (MW)	CO_2 emissions (kgCO_2/MWh)
1	15.00	8,895,000	14	465.92744
2	47.11	999,000	330	405.93243

As far as possible, these values have been derived from real-world data. Generation costs consist of the average full load variable costs registered for two power plants in Chile (Santa Marta and Nueva Renca) in January 2019 [234], which correspond to MSWLG and NGCC technologies, respectively. Investment costs are taken from [235], and represent the overnight cost for each technology. Concerning the CO_2 emissions per power plant at nodes 1 and 2, these values are calculated considering a typical heat rate for a gas turbine and a combined cycle gas turbine, respectively, multiplied by the corresponding emissions factor taken from [236]. Finally, each outcome is expressed in units per MWh.

At node 3, there are three groups of electricity residential customers (or communities) with different annual disposable income and willingness to devote money in energy production. This information is detailed in Table IV.3.

Table IV.3. Communities located at node 3 and their characteristics

Node	Community	Socio-economic classification	Number of customers	Customers annual disposable income (USD)	Willingness to devote money factor
3	1	Low Income	500	324,900	0.1
3	2	Medium Income	300	340,200	0.1
3	3	High Income	100	352,080	0.1

To build up Table IV.3., we have gathered representative socio-economic information related to income characterisation of inhabitants in Chile, which can be found in [237]. Particularly, the customers annual disposable income values in Table IV.3. consist of the upper bound for categories YPCE7, YPCE4, and YPCE3 of the equivalent autonomous per capita income intervals (in Spanish, Tramos de ingreso autónomo per cápita equivalente) multiplied by the number of customers (randomly selected), the model time horizon (12 months), the willingness to devote money factor, and the corresponding CLP/USD exchange rate[53].

There are three groups of residential electricity customers who interact within the market: low income customers (LIC), medium income customers (MIC), and high income customers (HIC). These groups of customers, or communities, may choose participating in energy production by carrying out either a community energy project or a distributed generation/net billing project. The details about these projects are shown in Table IV.4.

Table IV.4. Citizen participation in energy production projects details

			Community energy project		Net billing project	
Technology	Node	Community	Generation costs (USD/MWh)	Generation investment costs (USD/MW)	Generation costs (USD/MWh)	Generation investment costs (USD/MW)
Solar PV	3	1	0.01	2,020,000	0.01	3,285,000
	3	2	0.01	2,020,000	0.01	1,795,000
	3	3	0.01	2,020,000	0.01	1,887,000

As shown above, all communities may participate in energy production by using solar PV technologies. The generation cost for the community energy project is very low, as only some minor operations and maintenance costs are required. The investment cost for the projects is obtained from [201], and is the same for all communities. On the other hand, the generation cost considered for the net billing scheme is very low, but investment costs are different for each community, given that each group of residential customers only has access to a particular type of solar PV equipment with a specific cost, which depends upon the specific capacity and vendor. Lower-income communities have a lower energy

[53] The exchange rate used in this work is CLP/USD 0.00150, which corresponds to the value stated on the 22nd March 2019, according to OANDA.com

consumption level and lower access to capital. The investment costs therefore correspond to solar PV panels with an installed capacity of 1kWp, 3kWp, and 5kWp [238], for low-income, medium-income and high-income communities, respectively. The final values are converted into USD through the corresponding exchange rate and expressed in per-MW.

The details about the existing transmission lines in the network are shown in Table IV.5.

Table IV.5. Existing transmission lines portfolio

Line	From	To	Circuits	Length (km)	Tension (kV)	Reactance (p.u.)	Capacity (MW)	Investment cost (USD)
1	1	2	1	34.85	220	0.08	211.53	12,591,500
2	1	3	1	23.24	220	0.11	105.76	6,295,750
3	2	3	1	17.43	220	0.15	52.88	3,147,880

Data for line 1 is based on real-world data about a line in the Chilean national transmission system (Chena 220 – Alto Jahuel 220) [239,240]. Data for lines 2 and 3 is scaled from line 1 to represent lines with a lower capacity.

Additionally, the details about the candidate new lines portfolio, based on arbitrary modifications of the above table, are shown in Table IV.6.

Table IV.6. Candidate new lines portfolio

Line	From	To	Circuits	Length (km)	Tension (kV)	Reactance (p.u.)	Capacity (MW)	Investment cost (USD)
1	1	2	1	34.85	220	0.08	200	16,368,950
2	1	3	1	23.24	220	0.11	100	5,036,600
3	2	3	1	17.43	220	0.15	50	3,620,062

IV.3.2 Characterisation of the incumbents' problems

Considering all the aforementioned elements and data, the relationships among the incumbent's problems are characterised as shown in Fig. IV.2.

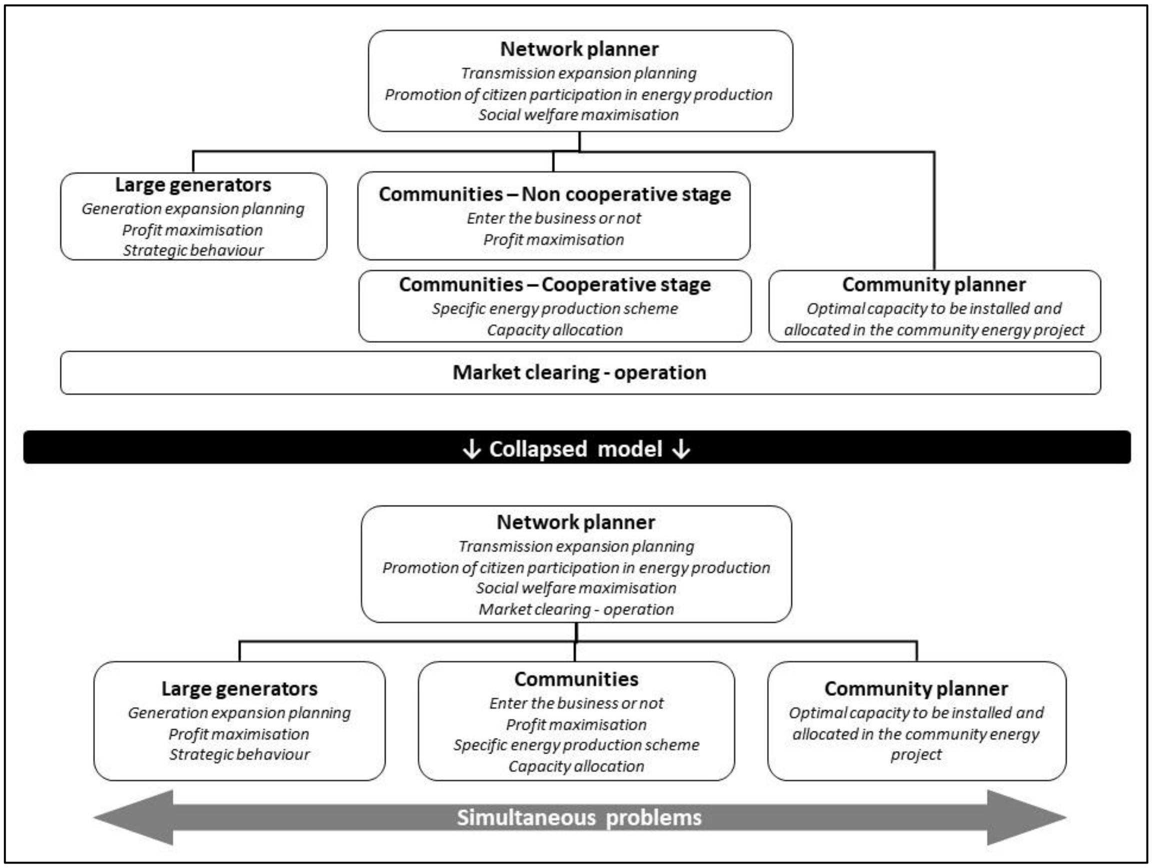

Fig. IV.2. Each incumbent's problem related to the market representation treated in this work

As shown in Figures IV.1. and IV.2., there is a network planner who wants to plan the transmission expansion of the system, taking into consideration a rational expectation of the expansion of the current two large generators' capacity and the inclusion of new citizen-led energy generation initiatives. Such citizen-led initiatives can be either a community energy project or a net billing scheme, which are in agreement with the definitions shown above in subsection IV.2.3. The market clearing (operation) occurs in a further (lower) stage, where the decisions about the expansion are taken, as can be seen on the top of Fig. IV.2. However, as shown in our collapsed model on the bottom of Fig. IV.2, for mathematical convenience, we assume that this network planner pursues social welfare maximisation while anticipating not only the generation capacity expansion, but also the market operation (clearing).

As mentioned beforehand, there are two large generators that maximise their profits. We assume they have perfect information about the demand at each node of the system and they strategically act and exercise market power in a Nash-Cournot fashion. Moreover, these generators can expand their current capacities, making rational expectations of the market operation for profit calculation purposes.

On the other side, there are three communities that consist of three groups of residential electricity customers with different disposable incomes. They can choose to participate in energy production by forming a coalition S={1,2,3}=I and using solar PV technologies within a community energy project or net billing scheme. They seek to maximising the profit of this project if they enter the business. These decisions can be seen on the top of Fig. IV.2., where communities face the non-cooperative part of their problem (game) related to the potential competition they might have with other initiatives or projects. However, they also need to invest in new installed capacity and allocate it among the customers that are participating in energy production. This implies deciding which initiative (community energy and/or net billing) is profit-maximising as well as stable (attractive), in the sense that no one would leave (change) the project or initiative. It is worth recalling that there is no initially installed capacity of such initiatives (in agreement with Fig IV.1.). These decisions can also be seen on the top of Fig. IV.2., where the cooperative part of the problem (game) related to the decisions about capacity/scheme (payoff) distribution is presented. These two stages, the non-cooperative and the cooperative one, are therefore collapsed and included within a same level (by modelling a biform game), as can be seen on the bottom of Fig. IV.2.

In parallel, another problem arises: how much money residential customers could potentially invest in energy generation? They have limited resources and do not have perfect access to financial markets, so this question is very relevant. To know so, a community planner sets a rule (by modelling a linear production game) that communities have to follow (solve) at the same time they evaluate the opportunity to participate in energy production. This rule establishes that communities need to take into account the costs, market prices, as well as their disposable income, in order to decide the optimal way to use their resources in energy generation (via a community energy project and/or net billing scheme). This rule also allows them to find an optimal maximum capacity to be invested, which ensure, at the same time, stability in the sense that no one would deviate or change that investment decision. From a more game-theoretical view, this way of modelling will allow to determine the maximum coalitional value to be distributed within the coalition and therefore facilitate the calculation of a solution under the core within one level.

Thus, conceptually speaking, the collapsed model (with just two levels) shown on the bottom of Fig. IV.2. is our proposed bi-level three-node optimisation problem. From a more mathematical viewpoint, it is important to note that the upper-level (network planner) problem is therefore modelled as a mixed-integer quadratic optimisation problem, which is solved considering the optimality conditions of the lower-level optimisation problems as constraints, together forming an MPEC. Since the upper-level problem is convex (i.e., a continuously differentiable concave objective function over a convex set) and the lower-level problems are also convex, it is possible to replace the lower level problems by their Karush–Kuhn–Tucker (KKT) conditions and include these conditions as constraints in the upper level. The KKT conditions are necessary and sufficient for lower-level optimality. We linearise the complementarity conditions using the Fortuny-Amat linearization method [241], for which the corresponding equations are shown in the Appendix.

The next section will outline the mathematical representation of the problems described above.

IV.3.3 Incumbents' problems formulation: a bi-level three-node optimisation model

Following what was shown in Fig IV.2. in a bottom-up view, the incumbents' equations that belong to our bi-level three-node optimisation model proposal are detailed as follows:

IV.3.3.1 Large generators model

Variables:

q_g^n = electricity produced by the large generator *g* located at node *n* (in MWh).

$g_{g\ exp}^n$ = new capacity installed by the large generator *g* located at node *n* (in MW).

Parameters:

a_d^n = demand curve at node *n* intercept.

β_d^n = demand curve at node *n* slope.

GC_g^n = variable generation cost for large generator *g* located at node *n* (in USD/MWh).

GIC_g^n = generation investment cost for large generator *g* located at node *n* (in USD/MW).

r = interest rate.

t = time.

q_g^{nMAX} = maximum installed capacity of large generator *g* located at node *n* (in MW).

Problem:

$$MAX_{\{q_g^n, g_{g\ exp}^n\}} \sum_n \sum_g \{ \ [\ (a_d^n - \beta_d^n q_d^n) q_g^n \ ] -$$

$$GC_g^n q_g^n - GIC_g^n g_{g\ exp}^n \left(\frac{1}{r} - \frac{1}{r(1+r)^t} \right)^{-1} \ \} \qquad \text{(IV.10)}$$

Subject to

$$g_{g\ exp}^{n} \geq 0 \Rightarrow -g_{g\ exp}^{n} \leq 0 \quad ({\mu_1}_g^n) \tag{IV.11}$$

$$q_g^n \geq 0 \Rightarrow -q_g^n \leq 0 \quad ({\mu_2}_g^n) \tag{IV.12}$$

$$q_g^n \leq q_g^{nMAX} + g_{g\ exp}^{n} \Rightarrow q_g^n - q_g^{nMAX} - g_{g\ exp}^{n} \leq 0 \quad ({\mu_3}_g^n) \tag{IV.13}$$

The KKT conditions for this problem are the following:

$$\frac{\delta L}{\delta q_g^n} \Rightarrow a_d^n - \beta_d^n q_d^n - GC_g^n + {\mu_2}_g^n - {\mu_3}_g^n = 0 \tag{IV.14}$$

$$\frac{\delta L}{\delta g_{exp}^n} \Rightarrow -GIC_g^n\left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)^{-1} + {\mu_1}_g^n + {\mu_3}_g^n = 0 \tag{IV.15}$$

$$0 \leq {\mu_1}_g^n \perp g_{g\ exp}^{n} \geq 0 \tag{IV.16}$$

$$0 \leq {\mu_2}_g^n \perp q_g^n \geq 0 \tag{IV.17}$$

$$0 \leq {\mu_3}_g^n \perp -q_g^n + q_g^{nMAX} + g_{g\ exp}^{n} \leq 0 \tag{IV.18}$$

IV.3.3.2 Community energy model (based on biform games)

Variables:

q_i^n = electricity produced by a community energy project owned by community i located at node n (in MWh).

$q_i^{n^{NB}}$ = electricity produced by a net billing scheme project owned by community (households) i located at node n (in MWh).

CEP_i^n = community i's installed capacity allocation based on a community energy project (in MW).

NB_i^n = community i's installed capacity allocation based on a net billing project (in MW).

Parameters:

α_i = community i's confidence index (continuous parameter $[0,1]$).

p^n = nodal price at node n (in USD/MWh).

GCC_i^n = community energy project generation costs for community i located at node n (in USD/MWh).

$GICC_i^n$ = community energy project generation investment costs for community i located at node n (in USD/MW).

p^{NB} = net billing injection price (in USD/MWh).

$GCC_i^{n^{NB}}$ = net billing project generation costs for community i located at node n (in USD/MWh).

$GICC_i^{n^{NB}}$ = net billing project generation investment costs for community i located at node n (in USD/MW).

$g_{i\ expected}^{nNB}$ = community i's expected individual installed capacity based on a net billing scheme (if they acted by themselves) (in MW).

$NBMax_{exp}^n$ = maximum installed capacity allocation based on a net billing project for communities located at node n (in MW).

$CEPMax_{exp}^n$ = maximum installed capacity allocation based on a community energy project for communities located at node n (in MW).

r = interest rate.

t = time.

q_i^{nMAX} = maximum installed capacity based on a community energy project for community i located at node n (in MW).

$q_i^{n^{NB^{MAX}}}$ = maximum installed capacity based on net billing projects for community (households) i located at node n (in MW).

Problem:

$$MAX_{\left\{q_i^n, q_i^{n^{NB}}, CEP_i^n, NB_i^n\right\}} \sum_n \sum_i \{ \alpha_i[p^n q_i^n - GCC_i^n q_i^n - GICC_i^n CEP_i^n (\frac{1}{r} - \frac{1}{r(1+r)^t})^{-1}] + (1-\alpha_i)[p^{NB} q_i^{n^{NB}} - GCC_i^{n^{NB}} q_i^{n^{NB}} - GICC_i^{n^{NB}} NB_i^n (\frac{1}{r} - \frac{1}{r(1+r)^t})^{-1}] \} \quad \text{(IV.19)}$$

Subject to

$$q_i^n \geq 0 \Rightarrow -q_i^n \leq 0 \quad (\mu_{1_i}^{c^n}) \quad \text{(IV.20)}$$

$$q_i^{n^{NB}} \geq 0 \Rightarrow -q_i^{n^{NB}} \leq 0 \quad (\mu_{2_i}^{c^n}) \quad \text{(IV.21)}$$

$$q_i^n \leq q_i^{nMAX} + CEP_i^n \Rightarrow q_i^n - q_i^{nMAX} - CEP_i^n \leq 0 \quad (\mu_{3_i}^{c^n}) \quad \text{(IV.22)}$$

$$q_i^{n^{NB}} \leq q_i^{n^{NB^{MAX}}} + NB_i^n \Rightarrow q_i^{n^{NB}} - q_i^{n^{NB^{MAX}}} - NB_i^n \leq 0 \quad (\mu_{4_i}^{c^n}) \quad \text{(IV.23)}$$

$$\sum_n \sum_i CEP_i^n = CEPMax_{exp}^n \Rightarrow \sum_n \sum_i CEP_i^n - CEPMax_{exp}^n = 0 \quad (\lambda_{2_i}^{c^n}) \quad \text{(IV.24)}$$

$$\sum_n \sum_i NB_i^n = NBMax_{exp}^n \Rightarrow \sum_n \sum_i NB_i^n - NBMax_{exp}^n = 0 \quad (\lambda_{3_i}^{c^n}) \quad \text{(IV.25)}$$

$$CEP_i^n + CEP_j^n \geq 0 \Rightarrow -CEP_i^n - CEP_j^n \leq 0 \quad (\mu_{5_i}^{c\,n}) \tag{IV.26}$$

$$NB_i^n + NB_j^n \geq g_{i\ expected}^{nNB} + g_{j\ expected}^{nNB} \Rightarrow$$
$$-NB_i^n - NB_j^n + g_{i\ expected}^{nNB} + g_{j\ expected}^{nNB} \leq 0 \quad (\mu_{6_i}^{c\,n}) \tag{IV.27}$$

$$CEP_i^n \geq 0 \Rightarrow -CEP_i^n \leq 0 \quad (\mu_{7_i}^{c\,n}) \tag{IV.28}$$

$$NB_i^n \geq g_{i\ expected}^{nNB} \Rightarrow -NB_i^n + g_{i\ expected}^{nNB} \leq 0 \quad (\mu_{8_i}^{c\,n}) \tag{IV.29}$$

The KKT conditions for this problem are the following:

$$\frac{\delta L}{\delta q_i^n} \Rightarrow \alpha_i p^n - \alpha_i GCC_i^n + \mu_{1_i}^{c\,n} - \mu_{3_i}^{c\,n} = 0 \tag{IV.30}$$

$$\frac{\delta L}{\delta q_i^{n^{NB}}} \Rightarrow (1-\alpha_i)p^{NB} - (1-\alpha_i)GCC_i^{n^{NB}} + \mu_{2_i}^{c\,n} - \mu_{4_i}^{c\,n} = 0 \tag{IV.31}$$

$$\frac{\delta L}{\delta CEP_i^n} \Rightarrow -\alpha_i GICC_i^n\left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)^{-1} -$$
$$\lambda_{2_i}^{c\,n} \sum_n \sum_i \frac{\delta L}{\delta CEP_i^n} + \mu_{3_i}^{c\,n} + \mu_{5_i}^{c\,n} + \mu_{7_i}^{c\,n} = 0 \tag{IV.32}$$

$$\frac{\delta L}{\delta NB_i^n} \Rightarrow -(1-\alpha_i)GICC_i^{n^{NB}}\left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)^{-1} -$$
$$\lambda_{3_i}^{c\,n} \sum_n \sum_i \frac{\delta L}{\delta NB_i^n} + \mu_{4_i}^{c\,n} + \mu_{6_i}^{c\,n} + \mu_{8_i}^{c\,n} = 0 \tag{IV.33}$$

$$\frac{\delta L}{\delta \lambda_{2_i}^{c\,n}} \Rightarrow -\sum_n \sum_i CEP_i^n + CEPMax_{exp}^n = 0 \tag{IV.34}$$

$$\frac{\delta L}{\delta \lambda_{3_i}^{c\,n}} \Rightarrow -\sum_n \sum_i NB_i^n + NBMax_{exp}^n = 0 \tag{IV.35}$$

$$0 \leq \mu_{1_i}^{c^n} \perp q_i^n \geq 0 \tag{IV.36}$$

$$0 \leq \mu_{2_i}^{c^n} \perp q_i^{n^{NB}} \geq 0 \tag{IV.37}$$

$$0 \leq \mu_{3_i}^{c^n} \perp -q_i^n + q_i^{nMAX} + CEP_i^n \geq 0 \tag{IV.38}$$

$$0 \leq \mu_{4_i}^{c^n} \perp -q_i^{n^{NB}} + q_i^{n^{NB^{MAX}}} + NB_i^n \geq 0 \tag{IV.39}$$

$$0 \leq \mu_{5_i}^{c^n} \perp +CEP_i^n + CEP_j^n \geq 0 \tag{IV.40}$$

$$0 \leq \mu_{6_i}^{c^n} \perp NB_i^n + NB_j^n - g_{i\ expected}^{nNB} - g_{j\ expected}^{nNB} \geq 0 \tag{IV.41}$$

$$0 \leq \mu_{7_i}^{c^n} \perp CEP_i^n \geq 0 \tag{IV.42}$$

$$0 \leq \mu_{8_i}^{c^n} \perp NB_i^n - g_{i\ expected}^{nNB} \geq 0 \tag{IV.43}$$

IV.3.3.3 Community energy planner model (based on linear production games)

Variables:

$CEPMax_{exp}^n$ = maximum installed capacity allocation based on a community energy project for communities located at node n (in MW).
$NBMax_{exp}^n$ = maximum installed capacity allocation based on a net billing project for communities located at node n (in MW).

Parameters:

α_{com} = communities average confidence index (continuous parameter [0,1]).

p^n = nodal price at node n (in USD/MWh).

p^{NB} = net billing injection price (in USD/MWh).

$\sum_{i \in S} R_{inv}(S)$ = coalition S's resources available (disposable income) for covering installed capacity investment costs (in USD).

$R_{inv\ NB}$ = net billing project investment costs or necessary resources to conceive 1 MW of a net billing project (in USD/MW).

$R_{inv\ n}$ = community energy project investment costs necessary resources to conceive 1 MW of a community energy project (in USD/MW).

r = interest rate.

t = time.

Problem:

$$MAX_{\{NBMax_{exp}^n, CEPMax_{exp}^n\}}\ \alpha_{com} p^n CEPMax_{exp}^n + (1-\alpha_{com}) p^{NB} NBMax_{exp}^n \quad \text{(IV.44)}$$

Subject to

$$[(\frac{1}{r} - \frac{1}{r(1+r)^t})^{-1}(\alpha_{com} R_{inv\ n} CEPMax_{exp}^n + (1-\alpha_{com}) R_{inv\ NB} NBMax_{exp}^n)] - \sum_{i \in S} R_{inv}(S) \leq 0 \quad (\mu_1^{cc\,n}) \quad \text{(IV.45)}$$

$$NBMax_{exp}^n \geq 0 \Rightarrow -NBMax_{exp}^n \leq 0 \quad (\mu_3^{cc\,n}) \quad \text{(IV.46)}$$

$$CEPMax_{exp}^n \geq 0 \Rightarrow -CEPMax_{exp}^n \leq 0 \quad (\mu_4^{cc\,n}) \quad \text{(IV.47)}$$

The KKT conditions for this problem are the following:

$$\frac{\delta L}{\delta NBMax_{exp}^{n}} \Rightarrow (1-\alpha_{com})p^{NB} - (1-\alpha_{com})\mu_{1}^{cc^{n}} R_{inv\ NB}\left(\frac{1}{r}-\frac{1}{r(1+r)^{t}}\right)^{-1} + \mu_{3}^{cc^{n}} = 0 \quad \text{(IV.48)}$$

$$\frac{\delta L}{\delta CEPMax_{exp}^{n}} \Rightarrow \alpha_{com}p^{n} - \alpha_{com}\mu_{1}^{cc^{n}} R_{inv\ n}\left(\frac{1}{r}-\frac{1}{r(1+r)^{t}}\right)^{-1} + \mu_{4}^{cc^{n}} = 0 \quad \text{(IV.49)}$$

$$0 \leq \mu_{1}^{cc^{n}} \perp \left[\left(\frac{1}{r}-\frac{1}{r(1+r)^{t}}\right)^{-1}\left(-\alpha_{com}R_{inv\ n}CEPMax_{exp}^{n} - (1-\alpha_{com})R_{inv\ NB}NBMax_{exp}^{n}\right)\right] + \sum_{i\in S} R_{inv}(S) \geq 0 \quad \text{(IV.50)}$$

$$0 \leq \mu_{3}^{cc^{n}} \perp NBMax_{exp}^{n} \geq 0 \quad \text{(IV.51)}$$

$$0 \leq \mu_{4}^{cc^{n}} \perp CEPMax_{exp}^{n} \geq 0 \quad \text{(IV.52)}$$

IV.3.3.4 Network planner model

Variables:

q_{d}^{n} = power load at node n (in MW).
fl^{n} = power flow from/to node n (in MW).
l_{exp} = new transmission line expansion (binary variable {0,1}).

Parameters:

TIC_{l} = investment costs of new transmission line l (in USD/line).
$PTDF_{l,n}$ = swing factors on line l related to power injection/withdrawal at node n.

th_l = thermal capacity of existing line l (in MW).

th_l^{new} = thermal capacity of new line l (in MW).

q_d^{nMAX} = maximum demand or peak load at node n.

r = interest rate.

t = time.

Problem:

$$MAX_{\{q_d^n, fl^n, l_{exp}\}} \sum_n \sum_g \sum_i \{ \int_0^{q_g^n + q_i^n + q_i^{n^{NB}} + fl^n} (a_d^n - \beta_d^n(q_d^n))\ dq_d^n - [\ GC_g^n q_g^n + (GCC_i^n q_i^n + GCC_i^{n^{NB}} q_i^{n^{NB}})\ ] - [\ \frac{1}{r} - \frac{1}{r(1+r)^t}]^{-1} [\ GIC_g^n g_{exp}^n + \left(GICC_i^n CEP_i^n + GICC_i^{n^{NB}} NB_i^n \right) + (TIC_l l_{exp})\ ]\ \} \quad \text{(IV.53)}$$

Subject to

$$q_d^n \leq q_d^{nMAX} \quad \text{(IV.54)}$$

$$p^n = a_d^n - \beta_d^n q_d^n \quad \text{(IV.55)}$$

$$\sum_n q_d^n - \sum_n \sum_g q_g^n - \sum_n \sum_i q_i^n - \sum_n \sum_i q_i^{n^{NB}} = 0 \quad \text{(IV.56)}$$

$$q_d^n - \sum_g q_g^n - \sum_i q_i^n - \sum_i q_i^{n^{NB}} - fl^n = 0 \quad \text{(IV.57)}$$

$$\sum_n fl^n = 0 \quad \text{(IV.58)}$$

$$-\sum_n PTDF_{l,n} fl^n \leq th_l + th_l^{new} l_{exp} \quad \text{(IV.59)}$$

$$\sum_n PTDF_{l,n} fl^n \leq th_l + th_l^{new} l_{exp} \quad \text{(IV.60)}$$

$$\text{Optimality conditions (IV.14) } to \text{ (IV.18)} \quad \text{(IV.61)}$$

$$\text{Optimality conditions (IV.30) } to \text{ (IV.43)} \quad \text{(IV.62)}$$

$$\text{Optimality conditions (IV.48) } to \text{ (IV.52)} \quad \text{(IV.63)}$$

IV.3.4 Specific assumptions and procedural considerations

Some assumptions and procedural considerations need to be taken into account in order to solve the optimisation problems outlined above.

First of all, as there are some differences in terms of units for some terms in all equations, all variables and parameters are converted to an hourly basis. Particularly, in terms of the investment costs for large generators and communities, including those for the community energy projects and net billing scheme projects, and new transmission lines, we assume that the corresponding incumbent would pay them back via an ordinary annuity considering an interest rate compounded hourly during the life cycle of a typical solar PV panel, which is 25 years in this case [121]. Thus, the hourly-basis interest rate $r = 0.1/8760$ and the number of payments or capitalisation periods $t = 25 \cdot 8760$ are included in the model as follows:

$$[\frac{1}{r} - \frac{1}{r(1+r)^t}]^{-1} = [\frac{1}{0.1/8760} - \frac{1}{(0.1/8760)(1+(0.1/8760))^{25\cdot 8760}}]^{-1}$$

Regarding the customers annual disposable income, denoted by $\sum_{i \in S} R_{inv}(S)$ in the model, this value corresponds to the sum of all customers' annual disposable incomes divided by 8760.

Secondly, the investment costs considered for installing 1 MW of a community energy project or a net billing scheme project, denoted by $R_{inv\ n}$ and $R_{inv\ NB}$ respectively, are the same as those presented in Table IV.4.

Thirdly, for simplicity, we assume that the best payoff that a community may get if it acts under another coalition $S \neq I \neq \{1,2,3\}$ is 0.

Fourthly, in order to consider and include, to some extent, the concept of fairness at the moment of allocating the capacity among communities, we consider a payoff allocation that is set out by the community planner based on how much each community might spend in new installed capacity for energy production, according to their available resources and the total resources that the coalition might have in total. Consequently, the community planner has the following two additional constraints:

$$CEP_i^n = \frac{R_{inv}(\{i\})}{\sum_{i \in S} R_{inv}(S)} CEPMax_{exp}^n \tag{IV.64}$$

$$NB_i^n = \frac{R_{inv}(\{i\})}{\sum_{i \in S} R_{inv}(S)} NBMax_{exp}^n \tag{IV.65}$$

Fifthly, from equations (IV.19) to (IV.52), which represent the communities and maximum capacity to be invested problems, it can be noticed that the parameter α_i is applied to both energy projects options, namely community energy projects and net billing scheme projects. This means that, under the formulation shown above, we assume that the best payoff comes from a community energy project and the worst one comes from a net billing scheme project. The rationale of this is that a community energy project would imply a higher installed capacity and, thus, the payoff would be higher as well.

Nevertheless, we carry out an alternative approach, by applying the parameter α_i to incomes and expenses, in order to reflect how confident the players are about the influence that incomes and/or expenses have on the final payoff and then on a specific strategy. This alternative approach therefore implies changes in some objective functions, constraints, and then KKT conditions as well. These alternative versions are shown as follows:

Alternative version of constraints (IV.30) to (IV.33):

$$\frac{\delta L}{\delta q_i^n} \Rightarrow \alpha_i p^n - (1-\alpha_i) GCC_i^n + \mu_{1\,i}^{c\,n} - \mu_{3\,i}^{c\,n} = 0 \tag{IV.66}$$

$$\frac{\delta L}{\delta q_i^{n^{NB}}} \Rightarrow \alpha_i p^{NB} - (1-\alpha_i) GCC_i^{n^{NB}} + \mu_{2\,i}^{c\,n} - \mu_{4\,i}^{c\,n} = 0 \tag{IV.67}$$

$$\frac{\delta L}{\delta CEP_i^n} \Rightarrow -(1-\alpha_i) GICC_i^n \left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)^{-1} - \lambda_{2\,i}^{c\,n} \sum_n \sum_i \frac{\delta L}{\delta CEP_i^n} + \mu_{3\,i}^{c\,n} + \mu_{5\,i}^{c\,n} + \mu_{7\,i}^{c\,n} = 0 \tag{IV.68}$$

$$\frac{\delta L}{\delta NB_i^n} \Rightarrow -(1-\alpha_i) GICC_i^{n^{NB}} \left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)^{-1} - \lambda_{3\,i}^{c\,n} \sum_n \sum_i \frac{\delta L}{\delta NB_i^n} + \mu_{4\,i}^{c\,n} + \mu_{6\,i}^{c\,n} + \mu_{8\,i}^{c\,n} = 0 \tag{IV.69}$$

Alternative version of constraints (IV.48) to (IV.50):

$$\frac{\delta L}{\delta NBMax_{exp}^n} \Rightarrow \alpha_{com} p^{NB} - (1-\alpha_{com}) \mu_1^{cc\,n} R_{inv\ NB} \left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)^{-1} + \mu_3^{cc\,n} = 0 \tag{IV.70}$$

$$\frac{\delta L}{\delta CEPMax_{exp}^{n}} \Rightarrow \alpha_{com}p^{n} - (1-\alpha_{com})\mu_1^{ccn}R_{inv\ n}(\tfrac{1}{r}-\tfrac{1}{r(1+r)^t})^{-1} + \mu_4^{ccn} = 0 \quad \text{(IV.71)}$$

$$0 \leq \mu_1^{ccn} \perp [(\frac{1}{r}-\frac{1}{r(1+r)^t})^{-1}(-(1-\alpha_{com})R_{inv\ n}CEPMax_{exp}^{n} - (1-\alpha_{com})R_{inv\ NB}NBMax_{exp}^{n})] + \sum_{i\in S} R_{inv}(S) \geq 0 \quad \text{(IV.72)}$$

As noted above, we also include the term α_{com}, which is the communities' average confidence index. This parameter consists of the average of all confidence indexes considered in our model. This is a basic way to merge each community's confidence index into just one global confidence index, which facilitates the computation and solution of the community energy planner model. We encourage further research in terms of finding the most appropriate way to merge different confidence indexes, which is beyond the scope of this work.

We first solve our bi-level three-node optimisation problem considering a base case for both approaches, taking into account all the parameter values listed above, and with $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$, $p^{NB} = 100$ USD/MWh, and $R_{inv\ NB}$ equal to the highest net billing investment cost listed in Table IV.4. We then further increase the competition between community energy projects and net billing schemes by considering the parameter $R_{inv\ NB}$ as the average of the net billing investment costs declared in Table IV.4; we therefore carry out simulations for both approaches modifying the following terms: players' confidence index (α_i), customers' (grand coalition) total disposable income ($\sum_{i\in S} R_{inv}(S)$), net billing injection price (p^{NB}), and investment costs for net billing projects ($R_{inv\ NB}$).

We solve the bi-level three-node optimisation problem using Julia© 1.0.3 with Gurobi© 8.1.

IV.4 Results

IV.4.1 Visual representation of results

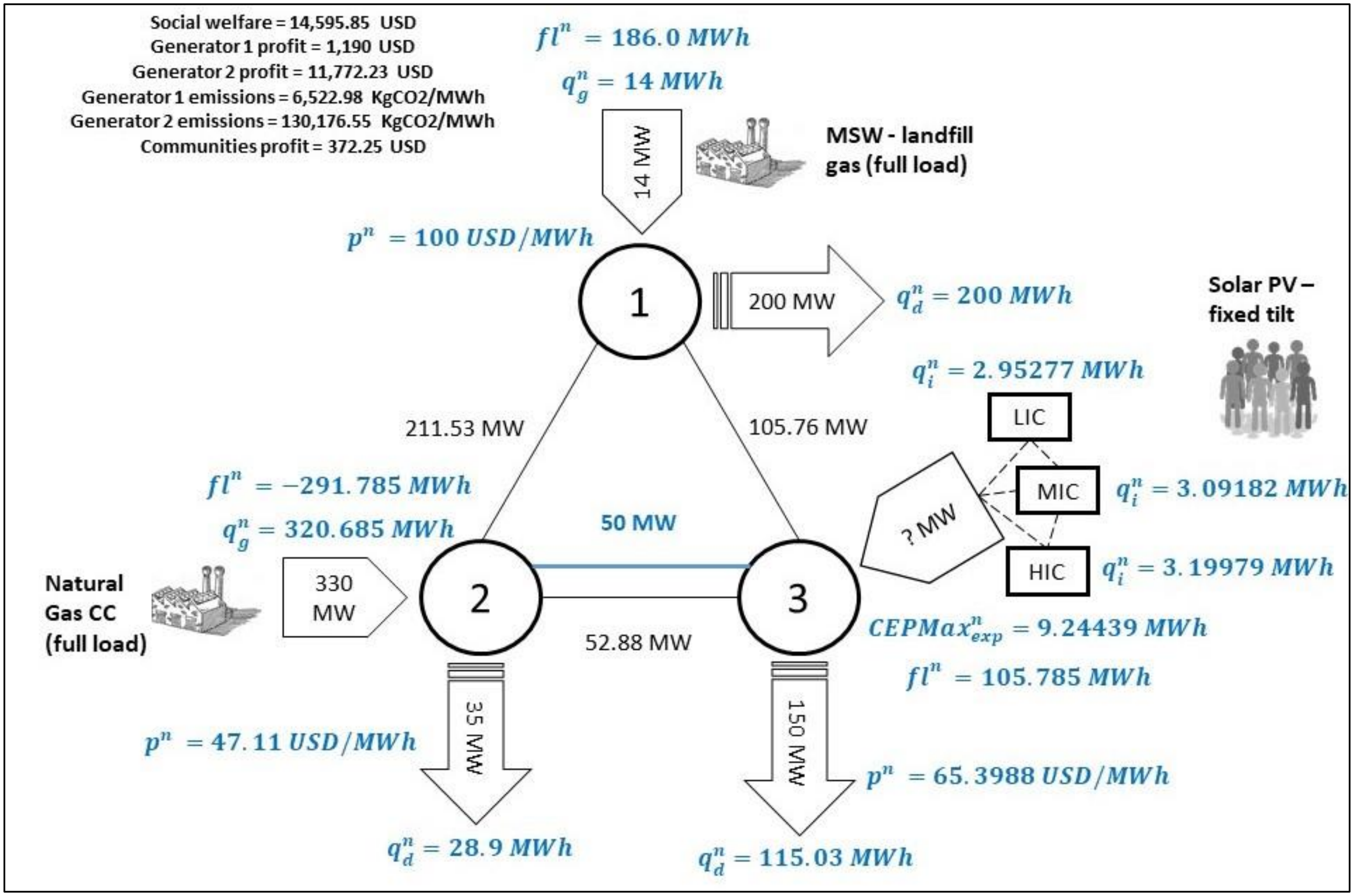

Fig. IV.3. Results for the base case considering both approaches (confidence index applied to schemes and income/expenses).

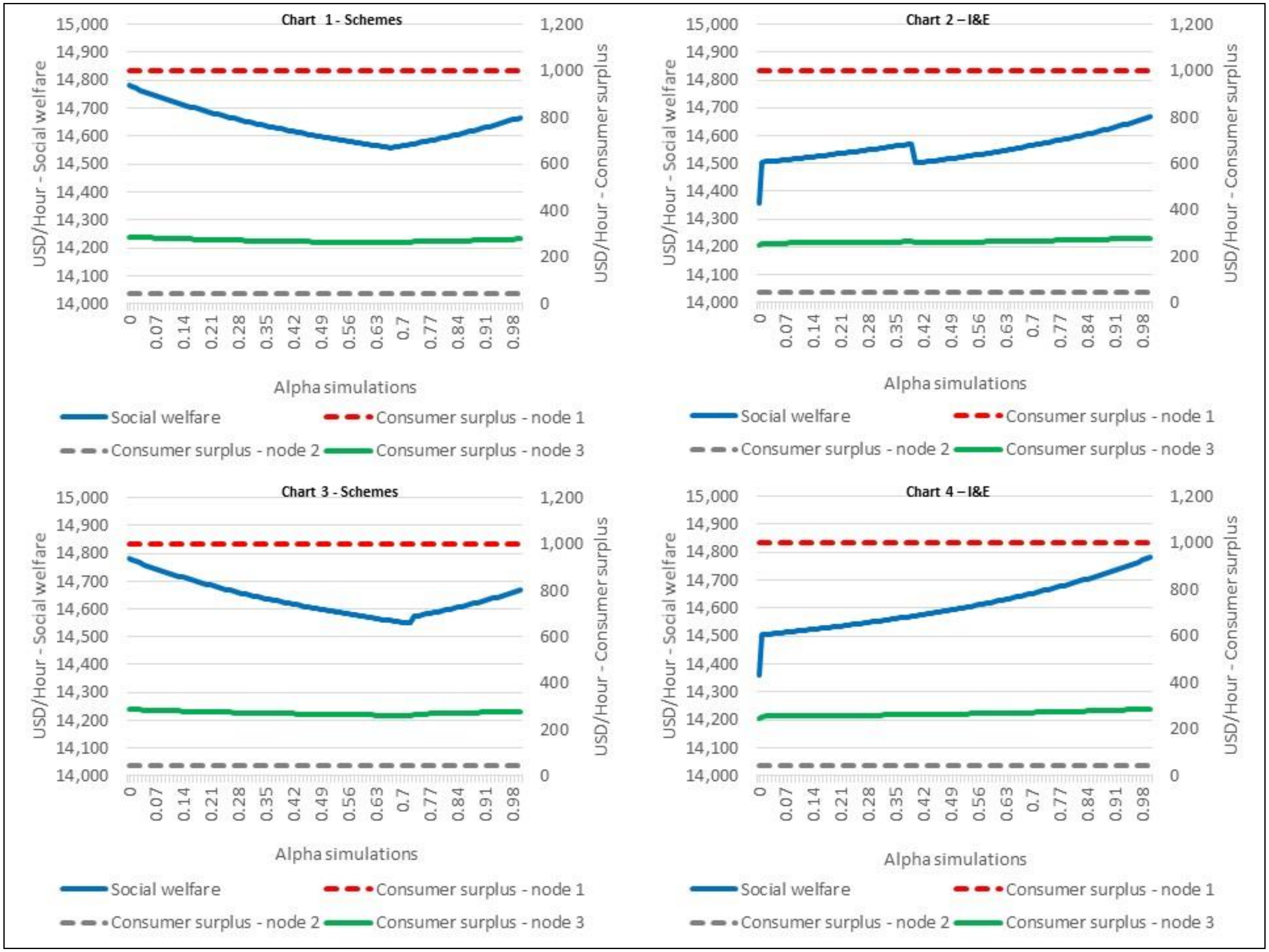

Fig. IV.4. Simulation results for parameter alpha (confidence index) considering $\alpha_1 = simulation, \alpha_2 = \alpha_3 = 0.5$, and $p^{NB} = 100$ USD/MWh on the top, and $\alpha_1 = simulation, \alpha_2 = \alpha_3 = 0.5$, and $p^{NB} = 50$ USD/MWh on the bottom. Alpha is applied to schemes (left-hand side) and income/expenses (right-hand side).

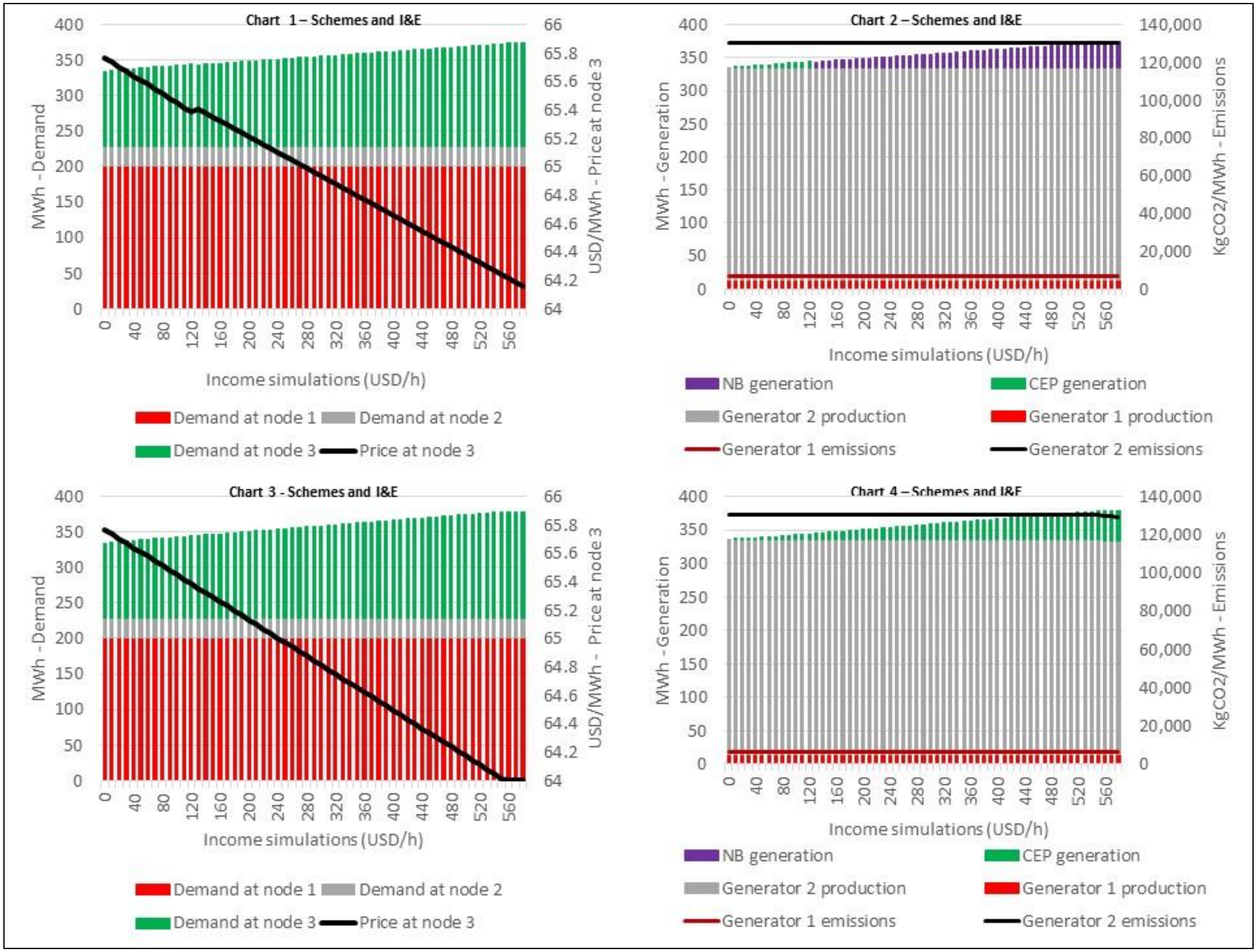

Fig. IV.5. Simulation results for customers total disposable income considering $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$ and $p^{NB} = 100$ USD/MWh on the top, and $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$ and $p^{NB} = 50$ USD/MWh on the bottom. Alpha applied to schemes and income/expenses shown on each chart (same results for both ways of applying alpha).

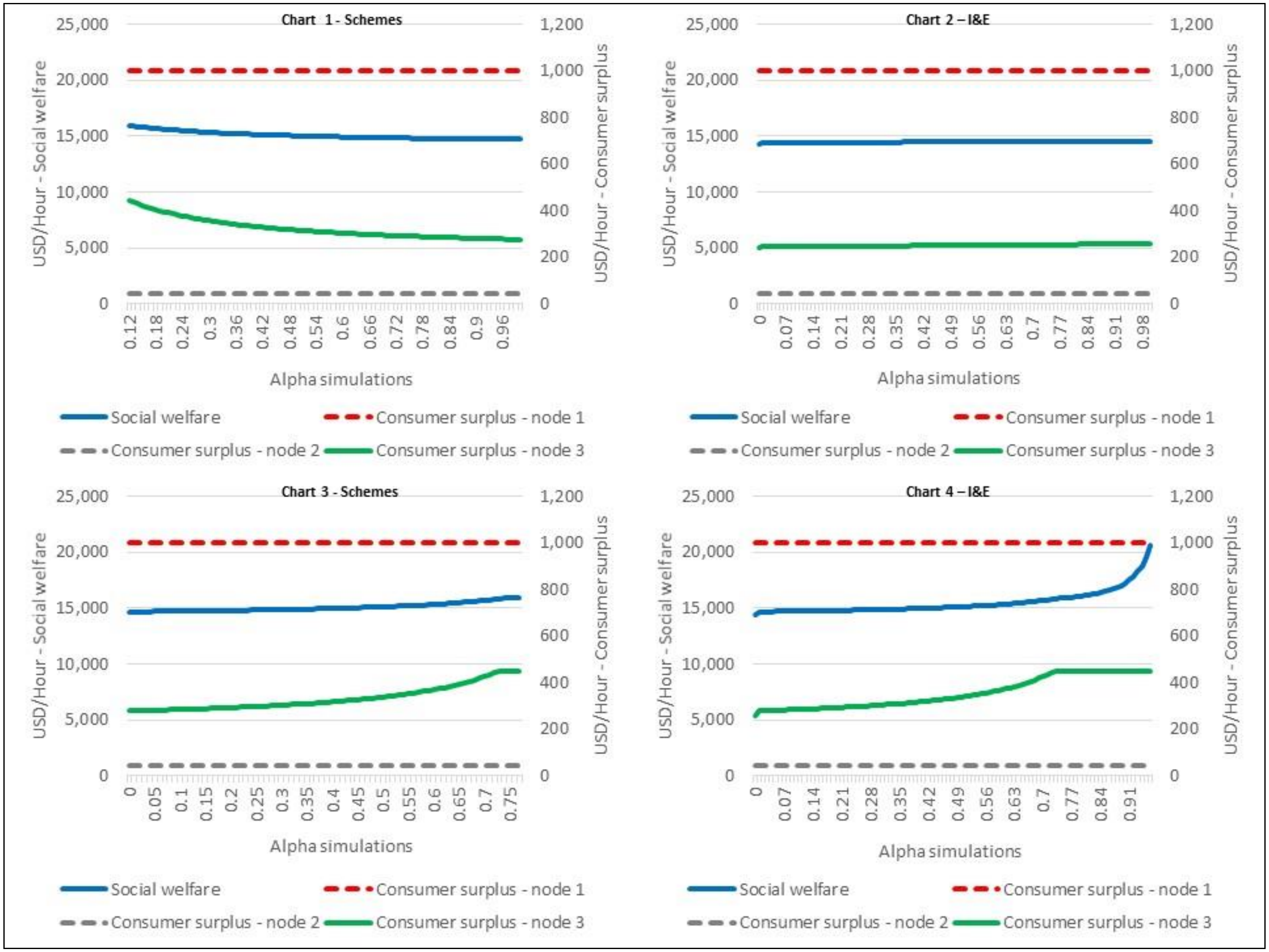

Fig. IV.6. Simulation results for alpha (confidence index) considering $\alpha_1 = simulation, \alpha_2 = \alpha_3 = 0.1$, and $p^{NB} = 100$ USD/MWh on the top, and $\alpha_1 = simulation, \alpha_2 = \alpha_3 = 1$ and $p^{NB} = 100$ USD/MWh on the bottom. Alpha is applied to schemes (left-hand side) and income/expenses (right-hand side).

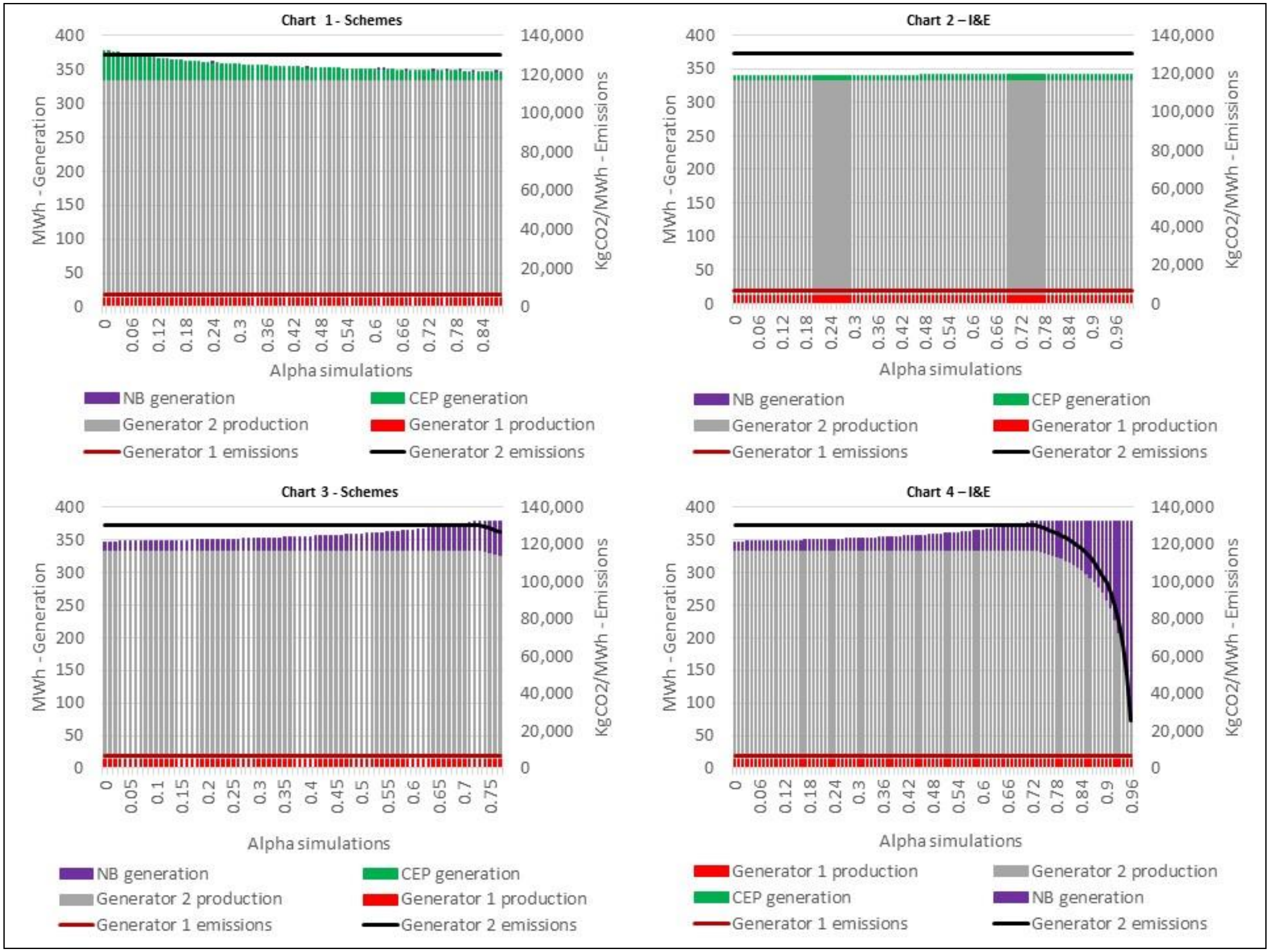

Fig. IV.7. Simulation results for alpha (confidence index) considering $\alpha_1 = simulation, \alpha_2 = \alpha_3 = 0.1$, and $p^{NB} = 100$ USD/MWh on the top, and $\alpha_1 = simulation, \alpha_2 = \alpha_3 = 1$ and $p^{NB} = 100$ USD/MWh on the bottom. Alpha is applied to schemes (left-hand side) and income/expenses (right-hand side).

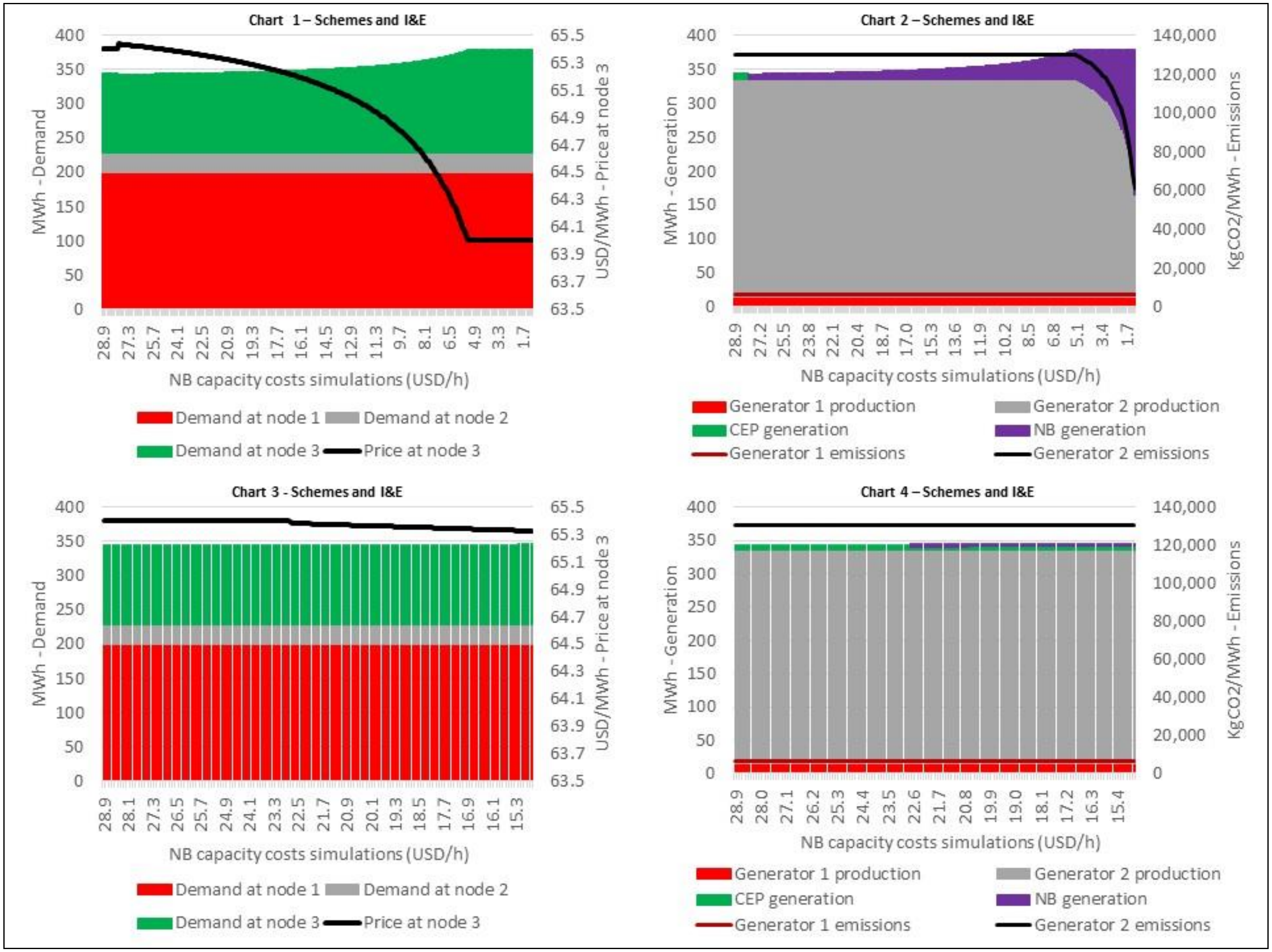

Fig. IV.8. Simulation results for net billing installed capacity costs considering $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$ and $p^{NB} = 100$ USD/MWh on the top, and $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$, $p^{NB} = 50$ USD/MWh, and a limit on net billing installed capacity of 4.5 MW for communities on the bottom. Alpha applied to schemes and income/expenses shown on each chart (same results for both ways of applying alpha).

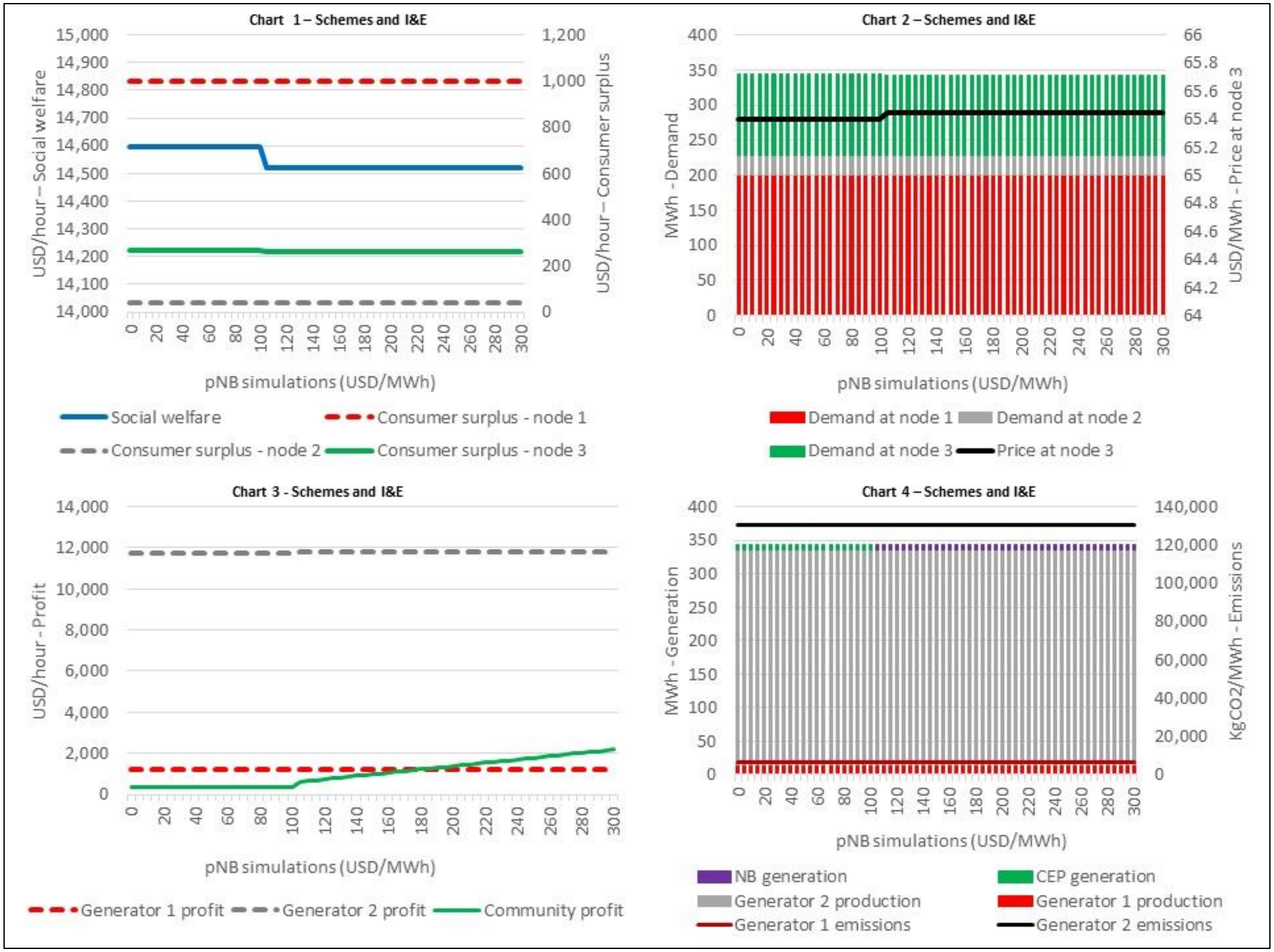

Fig. IV.9. Simulation results for net billing injection price considering $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$. Alpha applied to schemes and income/expenses shown on each chart (same results for both ways of applying alpha).

IV.4.2 Discussion

Fig. IV.3. shows the numerical results in the base case, which considers residential customers who are neither confident nor pessimistic about the potential result they can obtain within this game (i.e., $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$). From these results, it can be seen that there is an opportunity for community energy projects, even though a high net billing injection price of $p^{NB} = \text{USD } 100/\text{MWh}$ is available in the market. This happens because the investment costs for net billing projects is relatively higher. Moreover, it is not a surprise that the capacity allocation among all groups of residential customers is almost the same, given that we set out a specific (fairness) rule that enforces it. This should be understood as a way to prevent unfairness among the communities in the real world, which might lead to an exit from the grand coalition. In this sense, it is important to mention, again, that the core assures stability rather than fairness. This can be seen by the fact that the coalitional and individual rationality principles are met, as we assume that if customers act alone (out of the grand coalition) their payoff will be zero. This situation might not be true in some circumstances, and this requires further research into replacing the core constraints within the biform games and/or examine the potential payoffs that customers might get out the grand coalition. We left this extension as future work.

Another interesting result from Fig. IV.3. is that communities get a profit per hour when they enter the business, which is allocated according to the same capacity allocation rule shown above. This is very important for community energy projects as their nature is getting benefits that can be given to communities in order to benefit people. However, the role of the community energy project in this market is not enough to significantly deteriorate generator 2's importance and market power. As can be seen in the results above, the generator located at node 2 influences the market and electricity prices at each node, which can be seen, for example, in the new line that is built for delivering energy from node 2 to node 3, as well as the flows across the network and the corresponding prices. In addition, the highest profit goes to generator 2 and CO_2 emissions are not significantly reduced. In any case, we highlight the fact that, as long as people enter the business, this is profitable under a community energy project.

Fig. IV.4. shows the changes in social welfare and consumer surplus derived from changes in the low income residential customers' confidence index (α_1), keeping the remaining confidence indexes for medium and high income customers at a level of $\alpha_2 = \alpha_3 = 0.5$, respectively, and considering different net billing injection prices (particularly, $p^{NB} =$ USD $100/\text{MWh}$ and $p^{NB} =$ USD $50/\text{MWh}$). We note that there are some differences in the trajectory of the social welfare curve, if we use both approaches (confidence indexes applied to schemes and income and expenses, respectively). This can be seen where the curves change their slope and start increasing again, when $\alpha_1 = 1$. In parallel, it can be noted from Chart 4 of Fig. IV.4 that the social welfare does not have a similar kinked shape, but instead increases for all values of α_1 during the simulation. This can be explained because, in this case, there is no switch from community energy installed capacity to net billing installed capacity; on the contrary, the investment in a community energy project steadily increases as long as α_1 rises. The main factor here is that the net billing injection price is lower ($p^{NB} =$ USD $50/\text{MWh}$) so there is no incentive for communities to invest in a project that offers lower profits. However, in Chart 3 of Fig. IV.4, such a switch from one project to another happens because the confidence index is applied to schemes rather than income and expenses. Although the net billing injection price is also lower, a change in the confidence index more than compensates the gap, and therefore a switch happens. Nevertheless, we highlight that when the confidence index is applied to income and expenses considering a lower net billing injection price or, alternatively, when there is no switch from community energy projects to net billing projects, the social welfare is slightly higher than in the rest of the cases at the extreme (USD 14,781.55/h versus USD 14,666.71/h), when $\alpha_1 = 1$ and $\alpha_2 = \alpha_3 = 0.5$. At this point, the low income residential customers are totally confident whereas the rest of the customers within the grand coalition are neither pessimistic nor optimistic. Another interesting point is that when $\alpha_1 = 0$ and the confidence indexes are applied to schemes, the social welfare reaches its maximum. Oppositely, if the confidence indexes are applied to income and expenses then the social welfare reaches its minimum. In any case, the difference at this point in terms of magnitude is not highly significant (approximately USD 400/h). In both approaches, customers are generating energy through a community-led energy project at this point.

Fig. IV.5. shows the results for both approaches at the same time, as their results are very similar, noting the impacts on the demand at each node, price at node 3 (where the communities are located), generation at each node, and CO_2 emissions from generators 1 and 2. In this case, all residential customers are neither pessimistic nor optimistic ($\alpha_i = 0.5$) and two net billing injection prices are considered, as before, $p^{NB} = \text{USD } 100/\text{MWh}$ and $p^{NB} = \text{USD } 50/\text{MWh}$. Charts 1 and 3 show how a change in the customers' total disposable income affects the demand at each node and price at node 3. We clarify that the prices at nodes 1 and 2 remain the same during the simulation (USD 100/MWh and USD 47.11/MWh, respectively). As can be seen here, when the net billing injection price gets more competitive (i.e., when it drops) and there is a rise in the customers' disposable income, it is more attractive for the customers' coalition or grand coalition $S = \{1,2,3\} = I$ to invest in more installed capacity based on community energy projects, given the investment costs and the potential revenues they can obtain in the spot market. In the same vein, the minimum price at node 3 that electricity consumers who are outside the grand coalition (outsiders, from now on) might get is lower (USD 64/MWh versus USD 64.16/MWh). This implies that, in this case, community energy initiatives, in contrast to net billing, initiatives can also have positive effects on those that do not take part. This effect can also be seen in charts 2 and 4 where, as long as the income is high enough and prices are competitive, residential customers invest in community energy rather than net billing projects. This is more beneficial for the outsiders, as they save money when they consume electricity. In addition, Chart 4 reveals that when customers invest in community energy projects they can counter the market power exerted by generator 2 and decrease the CO_2 emissions in the market to some extent, as long as they have sufficient capital to do so. This is a relevant fact in comparison with the net billing alternative, as shown in Chart 2. This chart also notes that even with a low disposable income, the grand coalition would prefer to invest in community energy projects.

Fig. IV.6 and Fig. IV.7. show the effects on social welfare, consumer surplus, power generation, and CO_2 emissions derived from different extremes of confidence. Considering a net billing injection price of $p^{NB} = \text{USD } 100/\text{MWh}$, under a case that implies having medium and high income customers with confidence indexes $\alpha_2 = \alpha_3 = 0.1$, respectively, and another one with same customers but with $\alpha_2 = \alpha_3 = 1$, a simulation for the low income customers' confidence index (α_1) is performed. It can be noted in both figures that the aforementioned approaches (confidence indexes applied to schemes and income and expenses) give different results. If we take into account Fig. IV.6. applying the confidence index to schemes, we can highlight that the higher the low income customers' confidence, the more stable the social welfare gets (around USD 15,000/h) and the lower the consumer surplus at node 3 is (about USD 200/h), if $\alpha_2 = \alpha_3 = 0.1$. When the confidence index is applied to income and expenses, the consumer surplus at node 3 remains stable at the same level (about USD 200/h), again, if $\alpha_2 = \alpha_3 = 0.1$. On the other side, the more confident all customers are, the higher the social welfare and customer surplus at node 3 are. In fact, the grand coalition could potentially increase social welfare by almost 30% (when the confidence index is applied to income and expenses) and more than double the consumer surplus at node 3. This can be explained as follows. As can be seen in Fig. IV.7., there is no such level of confidence needed to carry out a community energy project, if we apply the confidence index either to schemes or income and expenses. The difference lies on the magnitudes. If the confidence index is applied to each scheme when we have $\alpha_2 = \alpha_3 = 0.1$, the communities' average confidence α_{com} tends to a low value and so the investment costs for community energy projects and the final capacity to be invested and distributed inside the coalition. This implies having a higher capacity of community energy generation in the market, however, this stabilises as long as α_1 converges to 1. When the confidence index is applied to income and expenses, the results reveal that it is profitable to conceive a community energy project even though the confidence and therefore the final installed capacity are very low. Nevertheless, this implies that there are limited options to counter the power exerted by the large generators, especially generator 2, and therefore no significant effects on prices and emissions, as can be noted in Chart 2. On the other hand, when the confidence is much higher and the net billing injection price is more attractive for potential generators, the grand coalition will invest in net billing projects, as shown in Charts 3 and 4. Of course, because there will be more local generation at node 3, there will be lower demand for more expensive electricity from other nodes so the price at node 3 decreases, demand and production at the same node (and within the system) increase, and CO_2 emissions from generator 2 exponentially decrease. However, according to the definition of net billing previously declared, we should have a huge installed capacity based on this type of projects, which consist of rooftop residential solar PV panels. This might be impractical in reality.

To clearly see the effects derived from the above-mentioned limitation in terms of the effective installed capacity that net billing projects, according to our definition, might have in reality, we perform an experiment leading to the results presented in Fig. IV.8. In Fig. IV.8, we assumed that all customers are neither optimistic nor pessimistic ($\alpha_1 = \alpha_2 = \alpha_3 = 0.5$). We firstly consider that there is a billing injection price of $p^{NB} = \text{USD } 100/\text{MWh}$. We carry out a simulation to see the effects on demand at each node, the price at node 3, generation at each node, and CO_2 emissions derived from a decrease on the net billing installed capacity costs. The corresponding results can be seen in charts 1 and 2. Then, we assume that there is a limit imposed by the community planner, in which customers within the grand coalition cannot exceed 4.5 MW of installed net billing capacity in total, which means that each customer (or household) cannot have more than 5kWp of installed capacity derived from rooftop solar PV panels. Given this limitation, the net billing injection price becomes more competitive to wholesale prices and reaches $p^{NB} = \text{USD } 50/\text{MWh}$. The corresponding results are shown in charts 3 and 4. It can be noticed in Fig. IV.8. that the aforementioned limitation obviously affects the net billing scheme deployment, a limitation that is arguably closer to the reality, and although such a limitation exists, there are still incentives to deploy both schemes at the same time, if the customers face lower costs. This helps increase competition and lower prices for the coalition members and outsiders; that is, for the entire market.

Finally, Fig. IV.9. takes into account a situation where all customers are neither optimistic nor pessimistic ($\alpha_1 = \alpha_2 = \alpha_3 = 0.5$) and the net billing injection price changes. This figure corroborates that a higher price reduces social welfare and this particularly happens when the residential customers or the grand coalition switches from a community energy project to a net billing project, even though the communities' profit significantly increases due to a higher injection price. This implies a very small increase of the spot price at node 3, as the production and demand slightly decrease, and no effect on CO_2 emissions.

IV.5 General remarks and recommendations

Considering the results shown above, we highlight that there are incentives to develop and deploy community energy projects, even considering the potential interactions they may have with other market participants, such as large generators that exert market power, net billing projects, etc. We demonstrate this by considering a novel methodology in electricity market modelling and, specifically, in generation and transmission expansion optimisation problems.

In determining the effects of community energy projects, the confidence index and the way it is applied are crucial in determining the optimal solution and equilibrium. Therefore a dilemma arises: how to apply the confidence index? Is the best option to apply it to schemes or income and expenses? According to the results obtained, we observe more conservative values in those cases where the confidence index is applied to income and expenses, putting prices and costs of both citizen participation in energy production options at the same level within a competition. This means, for example, that prices of both types of projects can be subject to the same confidence index at the same time to be chosen as the best option; if customers have a high confidence, so these prices take more relevance and become more important for the decision-making process in comparison with the costs. The opposite occurs when the confidence index is low so costs are more relevant. Thus, the confidence index can be interpreted as the confidence about how prices (income) or costs (expenses) influence the final outcome or payoff rather than a direct determinant of a weighted average payoff. Conversely, when the confidence index is applied to both schemes, the confidence index itself becomes more relevant and the decision-making process is mostly based on its magnitude or specific value rather than predefined prices and costs, especially when these two elements do not have a significant gap or distance between them. In this case, it is important to define which option may be catalogued as the "best" and "worst" one. This might be complex if the decision-making process is about choosing between two worthy options. To sum up, both approaches seem to be valid and therefore more research work is necessary to clarify this issue. Beyond the confidence index, the customers' disposable income is clearly important, as well as investments costs; changes to both can help increase citizen participation in energy production.

Accordingly, community energy projects are an attractive option to be considered as they offer stability and viability, from an economic-strategic perspective, as well as an interesting outcome, namely profits to be allocated. They also do not face, in principle, any significant limitation in terms of capacity in the same way net billing projects do, and do not need a high confidence and a very high (imposed) price ($p^{NB} = \text{USD } 100/\text{MWh}$) to be carried out. In this sense, regulated prices or subsidies for renewable energy projects seem to be less popular in many countries so projects with a direct involvement in the spot market could contribute to a deeper citizen participation in energy production. Concerning this, a key factor needs to be addressed in a more detailed way, namely, how people can fund or devote money to a community energy project. We consider mild assumptions in this work, but we encourage more research in order to design more advanced financial mechanisms or instruments that motivate people, under fair conditions, to get access to funding and then carry out a community energy project. Another important issue is that these models need to consider other variables, especially those related to social sciences, in order to produce more accurate outcomes in the near future, dealing with people's intentions, feelings, expectations, etc. One path could be how to measure the confidence index in reality using, for example, surveys with a Likert scale, interviews, or other social sciences tools.

A particularly interesting conclusion from our work is that community energy projects can have a positive impact even on those who do not participate in such projects. Again, this depends on the exact model parameters, but we find several cases where this happens, and where net billing distributed energy projects do not lead to the same result. This is an important outcome, which should be taken into account by policy makers, as positive externalities provide a justification for more support for community energy projects. Moreover, there is currently some concern that local energy developments can have negative impacts on lower-income households that do not participate in energy production initiatives; as we show, this concern may be valid but this effect can also go the other way, especially if community energy projects are considered.

Based on all the aforementioned elements, we provide some recommendations:

1. Design and evaluate more complex benefit allocation mechanisms that assure stability as well as fairness, considering models that deal with cooperative and non-cooperative behaviours at the same time, such as biform games.
2. Explore more options to provide better access to funding with proper and fair payback mechanisms, interest rates, uncertainty and risks assessments, among other elements.
3. Include social variables in this type of models in order to explicitly consider human behaviour in generation and transmission expansion planning optimisation problems.

4. Promote at a governmental level the use of this kind of model in order to better encourage, with a stronger financial and economic base, citizen participation in energy production.
5. Define clearer and more explicit goals and milestones related to the aforementioned points, in order to improve the community energy emergence discipline, taking into account a multidisciplinary perspective.

IV.6 Conclusions

This chapter proposes a bi-level generation and transmission expansion planning optimisation model, which attempts to evaluate the incentives for deploying community energy projects in real-world markets, addressing their interaction with other large generators and citizen participation schemes, such as net billing projects. This model combines biform games with linear production games in order to find stable and feasible solutions for the incumbents, from an economic and strategic perspective. As mentioned before, to the best of our knowledge, such inclusion and combination of these game theoretical tools has not been implemented yet, so we see many opportunities to further develop more research in the field of the community energy emergence as well as wider energy markets complexities.

Using real-world data, mainly considering the Chilean context, we model and solve a bi-level three-node generation and transmission expansion problem under mild assumptions. From our results, it is remarkable that community energy projects appear as an attractive option for residential customers to be involved in energy production, even when this option is economically disadvantaged compared to a net billing project with a higher (imposed) injection price. Community energy projects do not need a high confidence to be carried out, given their investment costs as well as the spot price they might obtain in the market. In any case, they might be jointly deployed with net billing projects as the latter would face a limitation in terms of the capacity that a household can bear. Besides, beyond the confidence index itself and its relevance, it is key the way how it is applied and used in the proposed model.

The results obtained might help countries around the world which would like to explore the idea of promoting citizen participation in energy production. This is especially true in those regions where the community energy sector is still unknown or incipient, so future research should further examine explicit public policies in order to tackle climate change, promote a sustainable development in countries around the world, foster a more democratic access to free markets and capitalism, reduce inequality and transfer more power to communities, etc.

FINAL REMARKS AND GENERAL CONCLUSIONS

In this doctoral thesis, the main features of the Scottish and Chilean citizen participation in energy production sectors have been shown, with particular focus on the community energy sector in both countries. This includes analysis of the current Chilean net billing scheme through non-cooperative games, in order to better understand its economic-strategic convenience for residential electricity customers. Furthermore, an exploratory assessment about the preferences for local energy initiatives based on solar PV technologies has been presented. This assessment was carried out by launching an online survey focused on residential electricity customers who live in Region Metropolitana (Santiago and its surroundings), Chile. Through social science tools, the customers' willingness to participate in such projects (by devoting time and/or money) was analysed, including a novel independent variable related to the customers' sense of ownership. Moreover, a pioneering, but simple game theoretical development was presented in this work, which considers the use of a novel tool in energy/electricity markets matters, biform games. Through such game theoretical developments, the economic-strategic viability of community energy projects was analysed and contrasted with other electricity provision schemes, including net billing. At the same time, this exercise dealt with games with a non-empty core and games with an empty core, which is relevant from a mathematical and economic perspective, as it would be possible to find an intuitive and reasonable solution no matter how the core is. Finally, in order to investigate the effects of community energy projects on the wider electricity system, a simple, but novel bi-level generation and transmission expansion planning optimisation model, which combines biform games and linear production games, has been presented. Given the nature of the economic problem behind such model, its formulation was developed as a mathematical program with equilibrium constraints (MPEC) problem, which involved determining the corresponding Karush–Kuhn–Tucker (KKT) conditions in order to find optimal solutions in a more efficient and accurate way.

Based on the data, evidence, and models formulated in this work, it is possible to highlight the following general conclusions:

1. The Scottish experience in community energy development should be catalogued as a remarkable example (to be followed), not only in terms of installed capacity but also in terms of the social organisations that are currently participating in such sector, which are benefitting people in a sustainable way.
2. The Chilean net billing scheme may not be the best support mechanism for citizen-led energy developments so other citizen participation in energy production schemes should be considered. Community energy projects can be the best strategy to follow for residential electricity customers in Scotland and Chile. Moreover, there are more opportunities for community energy projects to be implemented in comparison with net billing schemes in both countries, even when incumbents have uncertainty about their share of the project's benefits. Unsurprisingly, cost subsidisation can further improve community energy incentives.
3. Under more complex interactions within electricity markets, community energy projects might be competitive even when they are economically disadvantaged against net billing projects, bringing positive effects on social welfare, consumer surplus, nodal prices, and CO_2 emissions under specific circumstances.
4. The residential electricity customers considered in this work appear to be willing to participate in or devote money and/or time in local energy initiatives (based on solar PV technologies). However, at the same time, consumers are worried about the lack of financial resources necessary to fund those local energy initiatives.
5. Consumers' sense of ownership influences both willingness to devote time and willingness to devote money, which implies that who owns the project (a particular energy production scheme) matters.

The above-mentioned points and the specific content revealed in each chapter of this work lead to the following more general recommendations from a policy perspective:

1. If a higher citizen participation in energy production is desired, then the Chilean government should refocus the current strategy and policy to foster other types of initiatives such as community energy projects.
2. This would imply revising the current narrative around net billing projects and their preference, considering, at the same time, a shift towards long-term explicit goals in relation to the implementation and deployment of community energy projects across the country assuring, among other elements, low-cost access to the network (market).
3. Such a new narrative on the promotion of community energy projects should include specific, achievable, and verifiable tasks or activities and milestones.
4. It would be useful to investigate and, where necessary, correct any key factor that might be influencing the emergence of community energy projects, such as prices and costs structures, current laws and regulations, technologies, limitations and prohibitions, market power exertion and lobbying, etc.
5. Communities need to be able to access the necessary funding to carry out energy generation projects. At the same time, even when the funding is provided, the project has to operate in a sustainable way, which may involve getting a client portfolio including long-term contracts like Power Purchase Agreements (PPAs). Thus, communities should be supported at the time of entering and running the business. This implies delivering content related to finance, management, economics, energy generation technologies, law and regulation, at least at a basic level.
6. Community energy projects involve a variety of elements related to several fields of study, including history, psychology, sociology, economics, management, engineering, etc., so governments should promote multidisciplinary support to communities and electricity consumers in general, which should lead to fostering more independent, resilient, collaborative, supportive, and sustainable communities.

Regarding a more technical and future-research perspective, some recommendations can be given as follows:

1. All models presented in this work, with the exception of those ones shown in chapter two, should be extended to explicitly include social and environmental variables that take into account elements like willingness to participate in, sense of ownership, environmental externalities, carbon taxes, and so on, in order to refine the results and potentially get more relevant information for policy-making processes. In the same vein, other sharing/distribution rules based on biform games, for instance, should be included in order to design more innovative mechanisms that assure not only stability but also fairness. Of course, this might imply more challenges, and possibly a very high computational cost.
2. Especially relevant is the specific calculation of the confidence index and the way it is applied. In this sense, social science tools like Likert-scale-based surveys might help to improve the estimation of this parameter, which would enable a more accurate view of people's confidence over a particular economic-strategic interaction with other incumbents. This would lead towards a more accurate measure of the uncertainty and more evidence about which way is the best one to use the confidence index (over schemes or incomes and expenses).
3. Another significant research topic in the near future should be the way citizens can get the funding to participate in initiatives such as community energy projects. Accordingly, more sophisticated financial models should be developed to take into account more complex variables that help to determine a fair measure of risks and then a proper interest rate calculation with the corresponding payback conditions. This would be very important, as communities might not all face the same terms and conditions to access the capital, especially in comparison with larger companies that they compete with.
4. Further research addressing sociological, psychological, and other social variables, gathering more representative data to accurately describe the population, should be

carried out in Chile in the near term, in order to obtain a better idea about who would like to be involved in community energy initiatives and the implications of that. This would lead the development of novel tools, based on social and/or economic variables, to determine which scheme should be the proper one for a specific community.

This research has been a first attempt to describe Chilean citizen participation in energy production sector, with focus on community energy projects, taking into account international examples such as the Scottish community energy sector. Furthermore, using game theoretical tools, this work attempted to demonstrate that the current Chilean net billing scheme would not be convenient for residential electricity consumers who want to be involved in energy production. At the same time, this work has been a first attempt at investigating whether Chilean citizens would be willing participate in energy production initiatives or not, by devoting time and/or money, and how this depends on their sense of ownership of these initiatives. Moreover, this work has been a first attempt at applying biform games to energy/electricity markets matters, including their inclusion in more complex generation and transmission expansion optimisation problems, with the objective of characterising the Scottish and Chilean community energy sectors, as well as providing evidence about their economic-strategic viability and competitiveness.

The evidence presented in this work, should encourage further research and deeper involvement in community energy development, implementation, and deployment.

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APPENDIX – LINEARISATION OF COMPLEMENTARITY PROBLEMS UNDER THE FORTUNY-AMAT & MCCARL APPROACH

The complementarity inequalities (IV.16) to (IV.18) are linearised as follows:

$$0 \leq {\mu_1}_g^n \leq MU$$

$$0 \leq g_{g\,exp}^n \leq M(1-U)$$

$$0 \leq {\mu_2}_g^n \leq MU$$

$$0 \leq q_g^n \leq M(1-U)$$

$$0 \leq {\mu_3}_g^n \leq MU$$

$$0 \leq -q_g^n + q_g^{nMAX} + g_{g\,exp}^n \leq M(1-U)$$

The complementarity inequalities (IV.36) to (IV.42) are linearised as follows:

$$0 \leq \mu_{1i}^{cn} \leq MU$$

$$0 \leq q_i^n \leq M(1-U)$$

$$0 \leq \mu_{2i}^{cn} \leq MU$$

$$0 \leq {q_i^n}^{NB} \leq M(1-U)$$

$$0 \leq \mu_{3i}^{cn} \leq MU$$

$$0 \leq -q_i^n + q_i^{nMAX} + CEP_i^n \leq M(1-U)$$

$$0 \leq \mu_{4i}^{cn} \leq MU$$

$$0 \leq -q_i^{n^{NB}} + q_i^{n^{NB^{MAX}}} + NB_i^n \leq M(1-U)$$

$$0 \leq \mu_{5i}^{cn} \leq MU$$

$$0 \leq CEP_i^n + CEP_j^n \leq M(1-U)$$

$$0 \leq \mu_{6i}^{cn} \leq MU$$

$$0 \leq NB_i^n + NB_j^n - g_{i\ expected}^{nNB} - g_{j\ expected}^{nNB} \leq M(1-U)$$

$$0 \leq \mu_{7i}^{cn} \leq MU$$

$$0 \leq CEP_i^n \leq M(1-U)$$

$$0 \leq \mu_{8i}^{cn} \leq MU$$

$$0 \leq NB_i^n - g_{i\ expected}^{nNB} \leq M(1-U)$$

The complementarity inequalities (IV.50) to (IV.52) are linearised as follows:

$$0 \leq \mu_1^{ccn} \leq MU$$

$$0 \leq \left(\frac{1}{r} - \frac{1}{r(1+r)^t}\right)^{-1} \left(-\alpha_i R_{inv\ n} CEPMax_{exp}^n - (1-\alpha_i) R_{inv\ NB} NBMax_{exp}^n + \sum_{i \in S} R_{inv}(S)\right) \leq M(1-U)$$

$$0 \leq \mu_3^{ccn} \leq MU$$

$$0 \leq NBMax_{exp}^n \leq M(1-U)$$

$$0 \leq \mu_4^{ccn} \leq MU$$

$$0 \leq CEPMax_{exp}^n \leq M(1-U)$$