Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia.

This paper presents an assessment of the obstacles to the development of non-conventional renewable energy sources in Colombia. In the study, eleven barriers were included in three clusters: technical, social and economic. These barriers obstruct renewable energy sources from contributing to the electricity market in Colombia, mainly in its non-interconnected areas.

The energy sources analysed are solar photovoltaic power, wind power, biomass, geothermal and small hydroelectric power (less than 20 MW electricity). Obstacles and energy alternatives are included in an assessment model by means of Analytical Network Process. The method permits ranking the barriers and energy sources according to their influence in the network. That means, the more conflictive the obstacles and the more obstructed the energy sources, the higher their values. Four experts participated in the procedure representing different stakeholders in the electricity market of Colombia.

The research showed the most important barriers are costs of investment and operating, lack of public and private coordination and lack of development planning for renewable energy sources. The most influenced (hindered by barriers) sources are wind power and geothermal power. However, the experts did not fully agree on those results and differences are discussed. The paper ends with some recommendations for overcoming the main obstacles against the participation of renewable energy sources in the Colombian electricity market.

Keywords: ANP, Colombia, Renewable energy sources, Electricity market.

1. Introduction

Colombia is one of the main emerging economies of the South American continent with an ever growing energy demand. Electricity consumption is not only increasing but also changing from a matrix almost completely based on Hydropower, to a mix, where fossil fuels are ever more prevalent [1]. Furthermore, there is a large portion of the country's surface where electricity distribution cannot reach consumption, and diesel engines are mostly providing the demanded electricity supply.

To match the electricity demand and the interconnection of the pending country areas, a low carbon economy has been set as a strategic priority for the Colombian government [2]. To fulfil this objective, one of the main strategies is the use of renewable energy sources. These include conventional (i.e. hydropower) and the so-called non-conventional renewable energy technologies (FNCE by its initials in Spanish): Solar Photovoltaic, Wind, Small Hydro, Geothermal and Biomass power, among others.

The approval of law 1715 in May 2014 seeks to integrate FNCE into the national energy system. In order to do so, it tries to enhance their participation in the current electricity market and their penetration in the non-interconnected zones (ZNI by its initials in Spanish). However, in spite of this law, FNCE are still encountering different barriers against their development

In this paper, obstacles to the development of FNCE in the Colombian electric sector are identified and prioritised by means of the help of four Colombian experts and the implementation of Analytical Network Process (ANP).

1.1. Energy market in Colombia

1.1.1. *Energy demand and mix.*

According to the UPME (Mining and Power Planning Unit), Colombian primary energy consumption has increased more than 200% in the past 3 decades. As a matter of fact, it has increased from 205,150 GWh in 1980 to 454,260 GWh in 2012 [1] (last available data). However, the final energy consumption per unit of GDP has declined by 50% during this period. Hence, the country has made a noticeable effort in implementing energy efficiency measures while increasing its primary energy consumption.

In 2012 [1], fossil fuels provided approximately 78% of the domestic primary energy demand. Of this energy, 45% was used for transport, 22% for industry, 19% for residential use and 7% for the government and businesses.

1.1.2. *Electrical energy mix*

The Colombian electricity sector has a constantly evolving regulatory framework. Currently, generation and supply work under open market competition, while transmission and distribution remain as regulated monopolies [3]. Electricity consumption in 1975 was 11,275 GWh while during 2012 this consumption rose to 59,988 GWh. This represents an increase of more than 500% in 37 years [1]. The Colombian electricity mix is dominated by hydroelectric production, which used to represent around 80% until recently.

Due to the enormous water resource dependence of the country, and the weather phenomena "El Niño" and "La Niña" Southern Oscillation (ENSO), the contribution of hydropower electricity production can vary between 45% and 95% [4]. In 2014, hydropower accounted for 69.5% of the electricity production [1]. Thermal generation backs this variation in hydropower production. But, as electricity demand increases, thermal power plants are gradually supplying more and more electricity, accounting for 29.6% of the supply in 2014 [1].

1.1.3. *Interconnected systems and non-interconnected zones.*

The National Interconnected System (SIN by its initials in Spanish) connects 48% of the national territory and covers 95% of the population. The ZNI account for 52% of the country's area (17 departments and 1,441 municipalities) and 625 thousand people (see Fig. 1). Currently, these zones produce electricity mainly with diesel generators [5]. Moreover, ZNI are characterized by their important FNCE potential, and for being located at remote sites, often inaccessible and/or with great ecological and ethnic interest [6].

1.1.4. *Law 1715 for the integration of FNCE in the national energy system.*

As mentioned before, Law 1715, enacted in May 2014 [7] promotes the development and use of non-conventional energy sources (especially those from renewable sources), in the national energy system. This law establishes the legal framework for the use of FNCE and creates tax incentives for the investment in these kinds of projects. These are:

- Incentives for investment in FNCE projects in ZNI, which substitute diesel generation.
- Tax incentives:
    - Income tax deduction.
    - Value Added Tax (VAT) exemption for goods and services used in the development of FNCE projects.
- Tariff incentives: Exemption from payment of customs duties when importing machinery and equipment to be used in the development of new FNCE projects.
- Accounting incentives: Accelerated depreciation of assets.

Nevertheless, no incentives and tax exemptions have been applied until today because the regulation was still pending and not all incentives have been regulated yet.

- There is a lack of regulations for self-generation, sales of self-generated electricity and the maximum capacities for FNCE projects.

- A long bureaucratic process without clear parameters is required to certify FNCE projects.
- Specific regulation for the ZNI where the electricity surplus cannot be sold to the national grid.

Although law 1715 helps to overcome some barriers to the development of FNCE, such barriers are still present in Colombia. For instance, [6,8] emphasises the need of energy policy in Colombia in order to support expansions on the grid, development of renewable energy and to address market stability and sustainability. Moreover, this law was not intended to promote key policies or mechanisms that have been proved successful such as:

- Investment in the grid in order to overcome the technical challenges that will be generated by FNCE [9].
- Renewable purchase obligations for a percentage of the total traded energy [10].
- Procedures to adjust incentives to future market and technology situations [11].

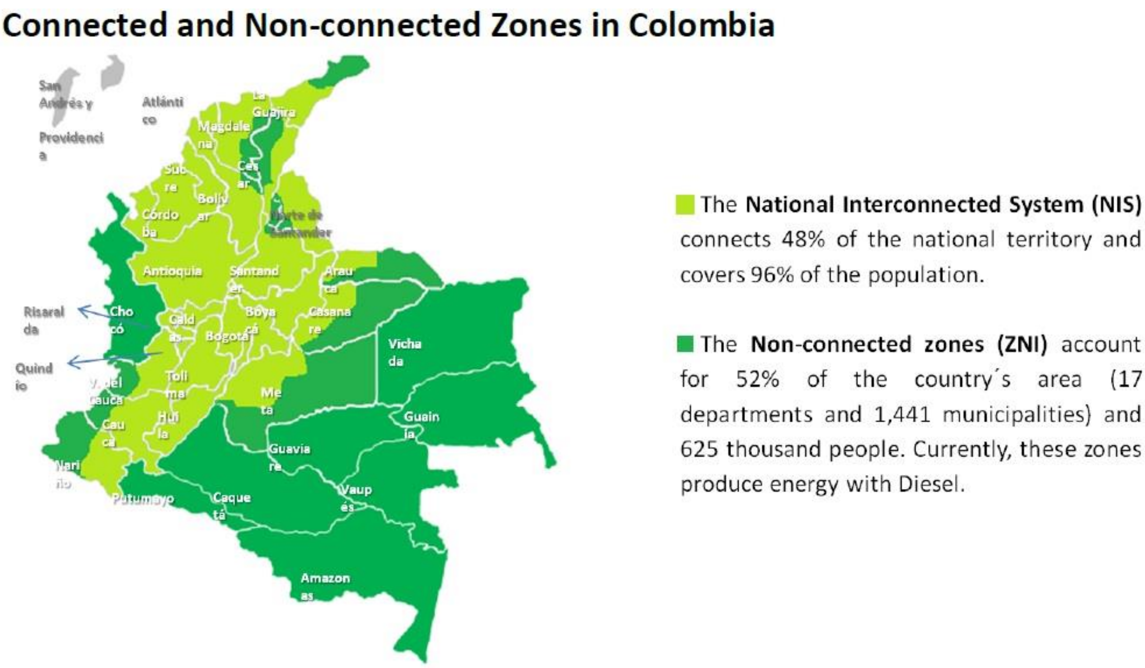

Fig. 1. ZNI and SIN (NIS) in Colombia [1].

2. Renewable energy sources

This chapter presents the FNCE with greater potential to penetrate in the Colombian electricity market. solar photovoltaic, wind, biomass (including solid waste), small hydroelectric and geothermal were chosen according to the literature review and with the agreement of the consulted experts [1,7,12,13]. On the other hand, solar thermal power does not contribute to the electricity market and is not supported by the authorities [1]. Tide and wave power and ocean thermal energy, although creating a growth of interest in Colombia, are neither present nowadays nor are there envisaged projects in the short term, despite their potential [1,14,15].

2.1. Wind power

The net installed wind generation capacity is 19.5 MW (2013) in only one power plant, which equals 0.1% of the country's total net generation capacity. Between 2010 and 2014, wind power produced an average of 52.2 GWh per year [3]. According to [1,15], wind energy potential could be converted into an installed capacity of up to 25 GW.

2.2. Solar Photovoltaic

Colombia has a high potential for solar energy and relevant opportunities because solar radiation throughout the country is mostly uniform during the year (average 4.5 KWh/m2/day). However, estimations made by [5,7], showed that the installed Colombian solar capacity was around 9 MWp by 2010. All of this capacity corresponded to private systems, business applications and solutions in ZNI (mostly formed by low capacity photovoltaic systems of less than 10 kWp). Estimations of the potential installable capacity for solar photovoltaic power were not found, but [16] analyses the solar radiation potential in some Colombian regions, although most of them are in the SIN area (see Fig. 1). Moreover, the steady decrease in capital costs and the advantageous equatorial situation have increased the interest for PV in Colombia. For instance, [7] have studied support schemes to promote the development of this technology in urban areas.

2.3. Biomass

In Colombia, biomass powered electricity accounted for about 804 GWh, equivalent to 1.3% of the electricity generated in 2013. Most of it was due to the energy use of sugar cane bagasse [17]. According to some researches, the installable capacity of biomass in Colombia could reach up to 15 GW [17], mainly in the ZNI where the majority of biomass is produced.

2.4. Geothermal

According to [1,3], the potential for electricity generation from geothermal resources in Colombia is estimated to be about 1-2 GW installed. These GW are only located in a few areas with enough potential, which are *Volcanes Chiles*, National Park of *Los Nevados*, *Paipa* geothermal area in Boyacá, etc.

2.5. Small Hydroelectric plants

Small hydro power (SHP) has been used in Colombia for more than 100 years [18]. It could be said that SHP, being renewable, need not be called non-conventional. However, the Colombian law 1715 of May 2014 includes SHP among non-conventional energy sources [2], and also various publications like [5,14] add SHP. Hence, it was decided to keep SHP among FNCE to align the research with the existing publications and national legislation, and to make its outcomes comparable with those of other related research (see table 1).

According to [5], small hydroelectric power has an estimated potential of 25 GW installed. Small hydro is the most competitive FNCE due to its early paybacks and reliable technology among other reasons. Thus, it is the most developed FNCE in both SIN and ZNI. Currently the installed capacity has reached 784.44 MW [1,18,19] in more than 200 plants (and many others non-connected to the grid), and there are various ongoing projects for increasing this amount.

3. Obstacles to FNCE development.

Colombia has an electricity matrix with a big renewable energy share because of hydropower. If other renewables were promoted, Colombia could almost reach 100% renewable electricity production [1,15]. However, despite the existing support programs and the announced ones, FNCE are almost testimonial in the electricity market. To identify the barriers preventing the development of FNCE, an extensive literature review was conducted. This literature review, and the following discussion of its outcomes with four experts, were part of the research methodology as will be explained in section 5. Nevertheless, the main findings are advanced here in order to explain how the obstacles to FNCE development were identified.

Of the several published research works found, the most helpful six have been summarized in table 1 (for a complete review of barriers to decentralized renewable energy systems see [20]). As can be seen, the countries under study were as diverse as China, Tanzania or UK. In any case, meaningful similarities were found. Those papers, together with others like [5,11,12] help to suggest a starting list of obstacles and a set of relationships with the list of renewable energy technologies. In the following sections, these starting lists are discussed and adapted to the case study.

Table 1.

Main findings in the literature review.

Research	**Country and Barriers found.**	**Renewable energy technologies**	**Method**
[21]	Turkey. • Lack of knowledge – Policy-makers – Potential consumers – Energy firms • Economic • Market culture	• Wind power • Hydropower • Biogas and biomass power, • Geothermal power, • Solar thermal power • Solar electricity power	Literature review and research on topic reports
[22]	India. 28 barriers grouped in 7 dimensions: • Economic and financial • Market • Awareness and information • Technical • Ecological and geographical • Cultural and behavioural • Political and government Issues	• Solar energy • Wind energy • Hydro energy • Geothermal energy • Biomass energy • Tidal power • Wave power	Analytical Hierarchy Process (AHP)
[23]	China. • The unbalanced development of regional economy • The scale barrier of renewable industry • The lagged construction of power grid • The lack of market base. • The inadequate incentive and supervision mechanisms	• Solar energy • Wind power • Hydro energy • Geothermal energy • Biomass energy	Literature review and research on topic reports
[24]	Mainly Canada, also UK and Denmark. 22 barriers grouped in 4 clusters: • Financial and legal hindrances • Physical hindrances • Ontological and social hindrances • Technological hindrances	Research works with “Renewable energy business” offering services with Biomass, Hydroelectric, Wind, Solar and Geothermal	Literature review and interviews
[25]	Tanzania and Mozambique. 37 obstacles grouped in 6 clusters: • Weak institutions and organizations • Economic finance	Not specified	Literature review and interviews

	• Social dimensions • Technological system and local management • Technology diffusion and adaptation • Rural infrastructure		
[26]	Australia. • Administrative hurdles • Problems for grid connection • Policy instability • Lack of social acceptance • Cost competitiveness • Govern support to conventional sources of energy.	Not specified	Literature review and research on topic reports
[1]	Colombia. • Subsidies for conventional sources. • High costs and financing difficulties. • Market barriers. • Scale economies. • Externalities • Lack of information • Lack of human capital • Technological prejudice, • Higher transaction costs • Regulatory and institutional factors	• Solar energy • Wind power • Geothermal Energy • Biomass energy	Literature review and research on topic reports

All those research works were a good reference although none truly represents the Colombian case. So, the findings of this research will contribute to completing the state of the art. On the other hand, only the work by [22] tried to rank the barriers. This makes sense as obstacles are numerous and varied and, according to the evidence, public resources to overcome them are scarce. Therefore, a rank order would contribute to efficiently assign public resources and efforts to the most significant barriers. Finally, in the literature, FNCE and barriers are generally related to each other in a general way, without assessing specifically which FNCE are more influenced and by which obstacles. The research in this paper aims to address this issue as well.

As mentioned, the work by [22] is the most similar to the paper's approach. However, it uses AHP and, hence, assumes an independence among barriers. This is a simplification of ANP, which is the method used in this research. ANP helps to identify and assess the mutual influences among barriers, and between barriers and FNCE. This way, their influence in the model, i.e. their importance, is more realistically assessed [27–29]. As far as the authors know, ANP has never been applied to modelling and ranking the barriers to the development of FNCE.

The work done by [1] is a main step forward and was discussed with experts on this topic. It contributed to update the statistical data and focus on the most concerning barriers. The report also includes a discussion on the relationship between FNCE and the identified obstacles. Nevertheless, it neither prioritises the obstacles, discussing all of them at the same level, nor does it rank the different FNCE based on their difficulties. Besides, it does not include Small Hydro because it finds it already competitive. Hence, this research presents a different approach, completing the analysis done in [1], allowing the prioritising of the FNCE and barriers in a scenario of limited available resources.

Once the barriers were documented, an initial list was elaborated with 32 barriers, most of them already listed in table 1, and the others are included in the following sections with their references.

That list was subsequently trimmed to a list of 16. With the second list, interviews with specialists and professionals were conducted and some of the obstacles were removed or combined with others. At the end, eleven barriers form the final list and have been classified into three clusters. All the barriers are presented and explained below.

3.1. CLUSTER 1: Technical barriers

3.1.1. *T1: Lack of electric grid in non interconnected zones (ZNI):*

As explained above, the Colombian electricity grid is not connected in more than 50% of the national territory, thus, it does not supply electricity to more than 625,000 people. Moreover, in many cases, these zones have a relevant renewable potential [6]. Consequently, it would be impossible to deliver electricity to the national grid and power plants could only deliver electricity locally. Something that would put the profitability of the investments at risk [1,12,17,30].

3.1.2. *T2: Customs tariff:*

No custom taxes need be paid when importing equipment for the development of new FNCE projects. Nevertheless, frequently these tax reductions are not applied to those materials since the custom officers do not distinguish between different types of material. As a consequence, investors have to pay taxes or complain, causing their material to be delayed [25,31].

3.1.3. *T3: Insufficient information about the potential of renewable energy sources:*

According to [5,17,31] there is a lack of geothermal, meteorological and renewable resources data. This absence of reliable data causes an increase in risks and costs. Investors must pay for accurate information and/or accept the risk of working with the available uncertain information.

3.2. CLUSTER 2: Economic barriers

3.2.1. *E1: Externalities:*

Conventional energies do not assume their environmental impact. If the environmental impacts were converted into costs and charged to conventional energy sources (gas, coal, diesel…), FNCE would automatically become more competitive. This barrier could be overcome with specific taxes to assign externalities [21,23].

3.2.2. *E2: Investment and operating costs (Levelised cost of electricity: LCOE):*

High capital cost is one of the main barriers to renewable energies. Among other reasons, equipment for renewable energy technologies has to be imported, increasing investment costs [31,32]. Besides, renewable electricity could have generation costs higher than market prices in some applications (some biomass projects for example). Therefore, LCOE are generally higher than in conventional power-generating assets, and subsidies are initially necessary in those cases [7,32].

3.2.3. *E3: Fossil fuels subsidy:*

Electricity generation in the ZNI zones has subsidies in Colombia. Due to their reliability and such subsidies, ZNI inhabitants normally receive diesel engines from the government. However, ZNI have a vast renewable potential and a high environmental value [6]. If donations and subsidies were switched to renewables, the latter energies would experience a faster development [33].

3.2.4. *E4: Undifferentiated electricity tariffs:*

The electricity price is determined by the spot market. Thus, every MWh is paid at the same price regardless of the type of generating technology or the geographical location. Consequently, electricity production tariffs are economically insufficient for developing technologies since FNCE have to compete on equal terms with conventional energy technologies such as coal, gas and hydropower. That is why, generally, renewable energy development plans include initial subsidies to production with FNCE [1,32].

3.2.5. *E5: Economies of scale:*

Renewable projects tend to be small compared to traditional power plants. Therefore, companies behind those plants have a lower capacity to trade with major consumers and to lobby in national policies [33].

3.3. CLUSTER 3: Social barriers

3.3.1. *S1: Lack of planning:*

The lack of planning is due to the inexistence of an applicable plan for FNCE development. Government states that FNCE are supported in the medium term but it does not explain how they are going to be promoted. For example, Law 1715 of 2014 does not have a complete technical applicable regulation yet [2]. Unfortunately, this situation is not specific to Colombia but quite common, as found in studies like [20,34]

3.3.2. *S2: Bad public-private coordination:*

The ministry responsible for electricity and renewable energies in Colombia makes decisions, issues specific rules and plans for the development of renewable technologies. However, according to two of the interviewed experts, it often acts without enough coordination and agreement of important stakeholders such as some private companies, non-profit making organizations, foreign investors or local communities. Again, this situation is also reported in other markets [20,34].

3.3.3. *S3: Insecurity related to armed attacks:*

Insecurity in rural regions (prevailing in ZNI), mainly if they are suffering from armed conflict, implies reluctance to invest there. These projects may have to assume not only insecurity but blackmail too.

It is important to bear in mind that recent efforts to reach a peace agreement between the Colombian government and armed guerrillas could radically change this environment. If this peace process ends in a positive way, this barrier will experience a drastic reduction on its impact. Particularly, it would have a wide effect on the ZNI, allowing both the public and private sectors to obtain more information about the potential renewable energy sources and invest in them.

4. Analytical Network Process methodology.

4.1. The method.

Barriers to FNCE are ranked by the ANP method, a type of multi-criteria aid for decision making (MCAD). MCAD methods have already proved to be successful for modelling complex situations with incomplete information and/or qualitative information, uncertain information, disagreement about information, etc. These methods assess and rank the elements of the model based on the influences amongst them. For instance, as previously explained, [22] applied AHP to rank barriers against FNCE development in India. Besides, scholars have applied ANP to model renewable energy policies [27]; investment in solar thermal projects [35]; energy planning [36]; selecting multiple criteria decision methods suitable for renewable energy planning [37]; choosing the most suitable renewable energy in Turkey [38]; and determining the location of wind farms [39], among others. All these examples show how MCAD has been widely used to help decision makers in complex environments such as energy planning and renewable energy development.

The Analytic Network Process (ANP) is a method proposed by [28] that provides a framework for dealing with decision making or evaluation problems. It is based on deriving ratio-scale measurements to allocate resources according to their ratio-scale priorities; whereas ratio-scale assessments, in turn, enable considerations based on trade-offs. ANP allows for complex inter-relationships among the decision levels using a network of criteria and alternatives, grouped into clusters. This provides an accurate modelling of complex settings and allows handling of the usual situation of interdependence among elements, as in the model of the barriers to the contribution of FNCE to the electricity market.

The ANP methodology is completely described in [28], however, the main steps are summarized here for completeness:

(i) Pairwise comparisons on the elements and relative weighting estimation.

The determination of relative weightings in ANP is based on the pairwise comparison of the elements in each level. These pairwise comparisons are conducted with respect to their relative importance towards their control criterion and measured using Saaty's 1-to-9 scale. The score of a_{ij} in the pairwise comparison matrix represents the relative importance of the element on row (i) over the element on column (j), i.e., $a_{ij} = w_i/w_j$ where w_i is the weighting of the element (i).

With respect to any criterion, pairwise comparisons are performed in two levels, i.e., the element level and the cluster level comparison.

If there are n elements to be compared, the comparison matrix (A) is defined as:

$$A = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & & w_2/w_n \\ \vdots & & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{pmatrix} = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \qquad (1)$$

After all pairwise comparisons are completed and the consistency of the matrix has been checked [28], the priority weighting vector (W) is computed as the principal eigenvector of the pairwise comparisons matrix.

(ii) Construction of the unweighted "supermatrix" (sic.).

The resulting relative importance weightings are placed within a supermatrix that represents the interrelationships of all elements in the system.

(iii) Constructing the weighted supermatrix.

The following step is based on weighting the blocks of the unweighted supermatrix, by the corresponding priorities of the clusters, so that it can be column stochastic.

(iv) Calculation of the global priority weightings.

Raising the weighted supermatrix to limiting powers until the weightings converge and remain stable the limit supermatrix will be obtained. In this matrix, the elements of each column represent the final weightings or prioritization of the different elements considered.

(v) Interpretation of the results.

The priority of each criterion (barrier) is a non-dimensional value. Based on the answers to the questions made to the experts, it will consider the influence of the barrier on the other barriers and on the alternatives. The higher the value, the more influential the barrier. Similarly, the non-dimensional values obtained for the FNCE represent how much they interact with other elements in the model, that is to say, how much they are affected by the barriers. Afterwards, the methodology based on ANP is explained, together with the case study.

5. Methodology and case study.

5.1. Description of the Evaluation Process

As Fig. 2 shows, this study was conducted in collaboration with a panel of experts, who represented different approaches to the problem:

- Expert 1: Representing the public administration: an expert midlevel official in the electricity sector of Public Enterprises of Medellín (EPM in Spanish). He belongs to the department of public relations. He has participated in projects of the electrical market, in coordination with various stakeholders. He also collaborates with a public university of Medelllín, and has cooperated with studies on the development of the electricity market in the ZNI.
- Expert 2: Representing the public business sector: a manager at the company Central Hydroelectric Caldas (Chec). He has a long experience in the commercial department of companies in the electricity sector. He has produced several reports of activity for his company, and has participated in diagnostic studies of the Colombian electricity sector, both public and private.
- Expert 3: On behalf of the scientific and academic sector a research professor at the National University of Colombia (public). He works in the areas of energy, climate change and mining. He is an expert in modelling, simulation and laboratory experiments for decision making. He has conducted research for companies and governments. His work has been published in indexed journals.
- Expert 4: Representing foreign investment (private): a Spanish entrepreneur owner of a renewable energy company in Colombia (confidential). He has worked for more than 20 years in the field of photovoltaic energy in South America and has experience in some projects in Colombia. He knows the electricity markets of Colombia and of its surrounding countries well, which gives him relevant comparative knowledge.

In ANP, due to the kind of information available, the quality of experts is more important than the number of them, as discussed in [24]. To be considered an appropriate expert for the research, requisites are: broad experience on the issue, personal research on the issue (demonstrable with publications), and to belong to a specific type of key actor related to the problem: companies, governments, academics, etc. Only the above listed experts were willing to participate in the research and fulfilled all the requirements. Unfortunately, other experts who could have enriched the outcomes were not available or not suitable. In order to prevent biasing the results, only one expert per stakeholder was selected.

The research team played the role of the ANP facilitators, participating in the decision-making process; that is, assisting the stakeholders in the evaluation and discussion of results throughout the entire procedure.

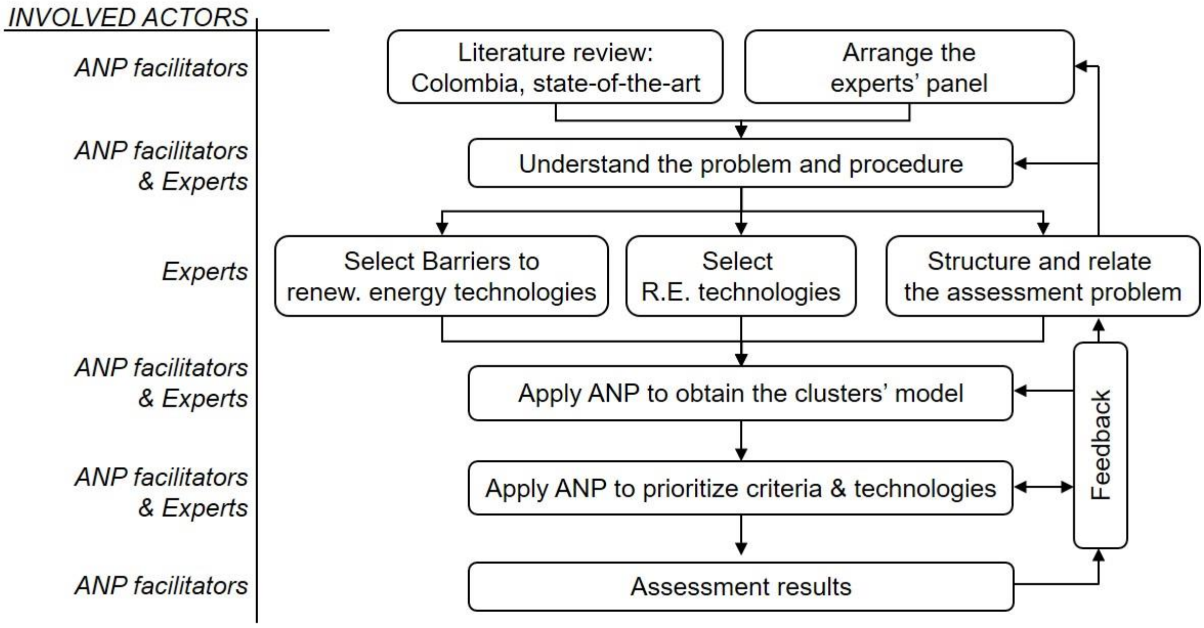

Fig. 2. Assessment procedure.

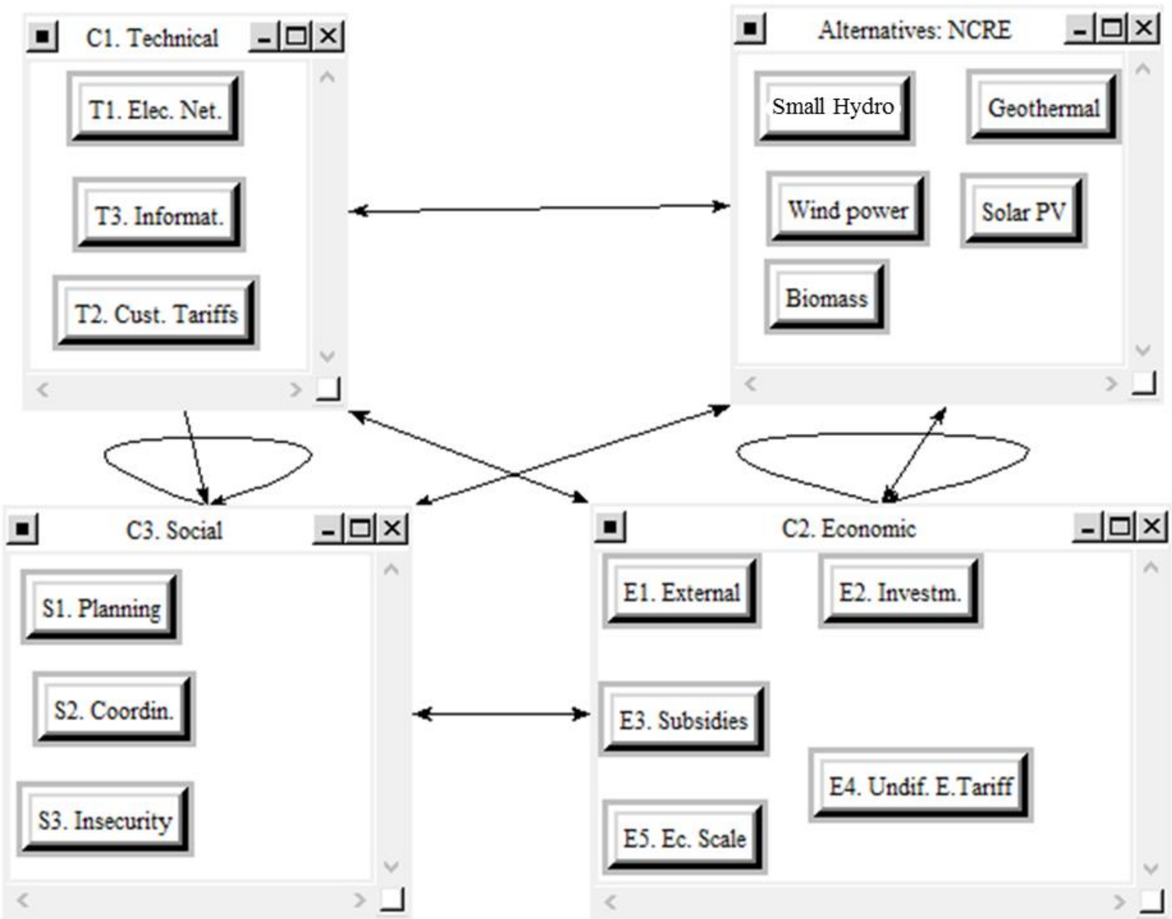

Fig. 3. Barriers and alternatives model by means of software Superdecisions®.

The first stage of the methodology was the literature review (advanced in section 3) and the arrangement of the experts' panel (explained in section 5.1.). After that, several meetings were held to discuss and understand the research goal, scope and procedure and set a working schedule. Once all agreed, three main activities took place in parallel. On the one hand, the first list of barriers was discussed and refined to adapt it to the Colombian case and the ANP methodology. On the other hand, FNCE were discussed and a consensus reached about which ones to include in the research. Finally, the network model was developed with the aid of Superdecisions® (see Fig. 3). Two way arrows indicate bidirectional influences between clusters, i.e., the elements of one cluster (*i*) exert some influence on those of another cluster (*j*), and vice-versa. The Feedback arrow means that there are influences among the criteria within a cluster.

In the next step of the procedure each expert went through an interview based on a questionnaire. The questionnaire required respondents to: (i) compare clusters against clusters; (ii) compare criteria against criteria; (iii) analyze each alternative against the barriers under study; and (iv) compare alternatives with alternatives (see example of its questions in Fig. 4). Answers to the questions were transferred to the software to fill in the pairwise comparison matrices in the model.

If EIPR barrier is Insufficient information about the potential of NCRE,

*Has **EIPER** more influence on the alternative **A2: Hydro Power** (less than 20 MW) or on the alternative **A3: Wind Power**? It means EIPR acting more as a barrier on A2 or on A3.*

In which is it more influent?	☐ A2	☒ A3			
How much?	☐Equal	☐Moderately	☒Strongly	☐Very strongly	☐Extreme

Fig. 4. Example of question from the questionnaire completed by stakeholders.

According to the ANP procedure, the consistency of all the pairwise comparison matrices has to be checked. Anytime the inconsistency of the matrix was bigger than 10%, the judgments were reviewed with the expert. Moreover, individual results of the evaluation model were shown to the experts in order to verify that they were meaningful to them and represented their preferences. If experts did not feel so, the questionnaires were reviewed and answered again.

Finally, the experts' judgements were aggregated using the geometric mean, as outlined in Saaty's methodology [28]. This process yielded the individual pairwise comparison matrices and supermatrices. Those results are discussed in the next section.

6. Discussion of results.

The limit supermatrix, normalized for each expert, was computed according to the ANP methodology. Table 2 shows the results for each expert and the aggregated (geometric mean). Note that the values were normalized in two general groups: Barriers and FNCE. Fig. 5, 6, 7 and 8 show results for barriers per expert, aggregated values for criteria, results for FNCE per expert, and aggregated values for FNCE more clearly.

Table 2.

Normalized limit supermatrix.**Criteria**/**Alternatives**		**Manager public company**	**Public official**	**Academician**	**Private businessman**	**Aggregated**
CLUSTER 1: Technical Barriers	T1: Lack of electric grid in ZNI	0.10	0.04	0.12	0.02	**0.07**
	T2: Customs tariff	0.06	0.15	0.06	0.17	**0.11**
	T3: Insufficient information about R.E. potential	0.05	0.02	0.03	0.01	**0.03**
CLUSTER 2: Economic Barriers	E1: Externalities	0.03	0.05	0.05	0.05	**0.04**
	E2: Investment and operating costs	0.18	0.23	0.17	0.15	**0.18**
	E3: Fossil fuels subsidy	0.06	0.10	0.06	0.10	**0.08**
	E4: Undifferentiated electricity tariffs	0.10	0.03	0.06	0.07	**0.06**
	E5: Economies of scale	0.06	0.05	0.10	0.02	**0.06**
CLUSTER 3: Social Barriers	S1: Lack of planning	0.16	0.06	0.11	0.13	**0.12**
	S2: Bad public-private coordination	0.14	0.05	0.13	0.16	**0.13**
	S3: Insecurity related to armed attacks	0.08	0.22	0.10	0.10	**0.11**
FNCE	Biomass	0.15	0.28	0.21	0.19	**0.22**
	Wind power	0.26	0.25	0.22	0.17	**0.24**
	Geothermal	0.25	0.25	0.22	0.16	**0.23**
	Small Hydro	0.15	0.08	0.12	0.23	**0.13**
	Solar PV	0.19	0.15	0.22	0.25	**0.17**

As can be seen in Figs. 7 and 8, results are more unevenly spread across barriers than across FNCE. Besides, there are clear differences between experts for some of the elements, and clear agreements in some others. These differences show how some stakeholders express a greater concern to some barriers than others, and these barriers are not always the same ones. For instance, only the public official assigns a large impact to “S3: Insecurity related to armed attacks”. During the interview, this expert mentioned several armed attacks on the public grid while the other experts were not as concerned as this one. In other applications on multiexpert ANP, consensus is needed and thus, further processing of results by experts is carried out to obtain the final outcome. In this case, the outcomes need not be consensualised, and differences among experts can be treated aggregating the results to calculate an average value.

Aggregated results show, as expected, the economic barrier “E2: Costs of investment and operating” is the most influential (see Fig. 5). All experts agreed on that, and agreed on giving relatively little importance to the other economic obstacles. Social obstacles were found to be very important on average, but there was not an agreement on them. Finally, only “T2: Ineffective customs tariff exemption for FNCE equipment” was found to be important on average within the Technical cluster, but there was not an agreement on that either. These differences show how not all stakeholders are affected by the same barriers. Those differences are another meaningful result of the procedure.

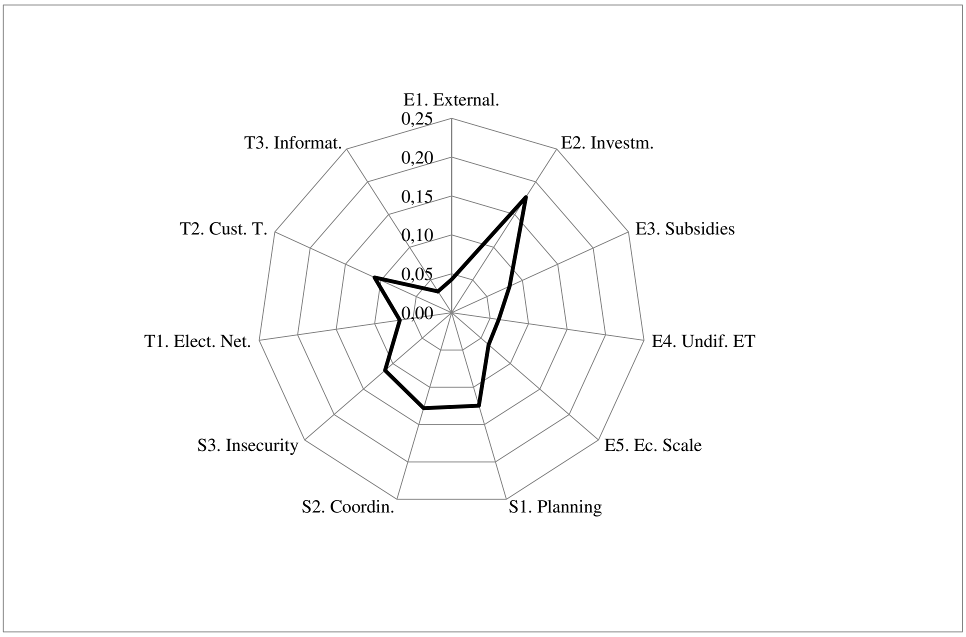

Fig. 5. Aggregated results for barriers.

About FNCE, unexpectedly, wind power was deemed as the most influenced by the barriers, along with the geothermal one (see Fig. 6). When experts were asked about it, they found the result understandable. However, there were different reasons for the results. As shown in Fig. 9, Wind power is more affected by technical barriers T1 and T2, related to electricity supply to the market. Geothermal power, however, needs support related to barriers “T3: Insufficient information about renewable energy potential”. Finally, as expected, small hydro was considered the least affected FNCE although the private businessman dissented from that.

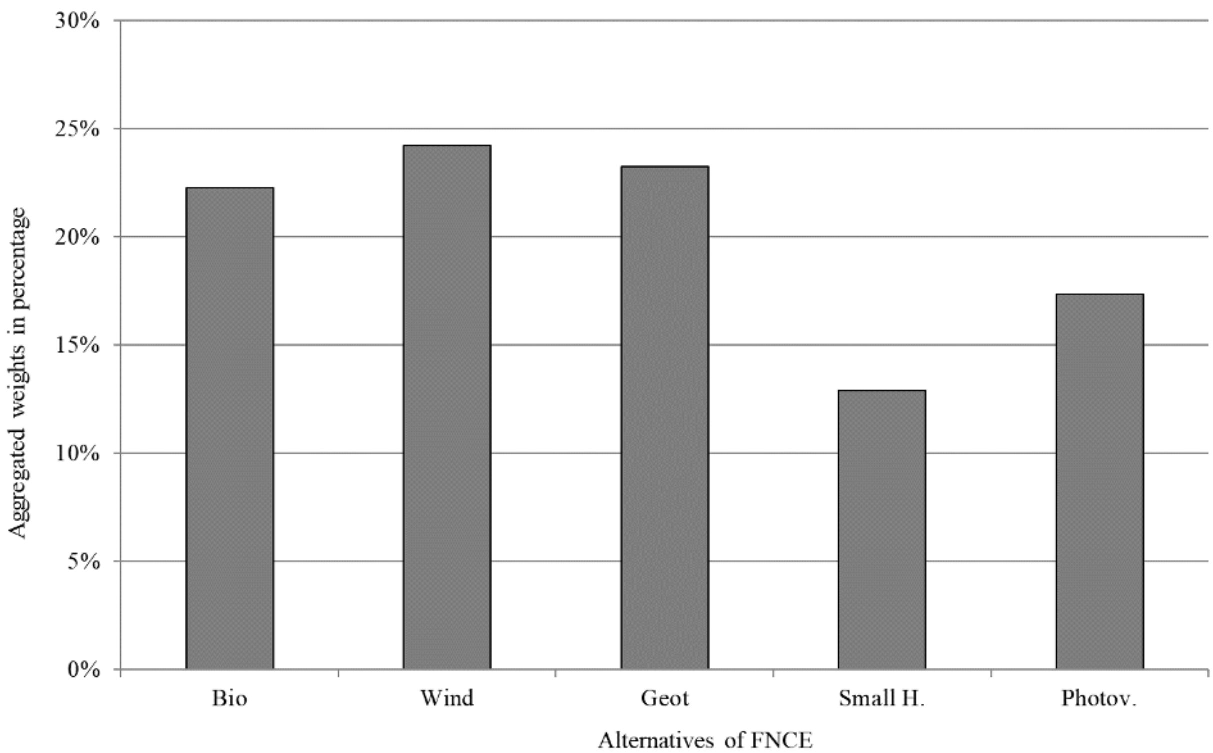

Fig. 6. Aggregated results for FNCE.

Separated results per expert show how the Manager of a public company and the academic obtained a similar profile regarding the barriers, except for the social cluster (see Fig. 8). The academic showed a preference for obstacles: “E2: Costs”, “T1: Lack of grid” and “S2: Bad coordination”, while the manager showed preference for the social barrier “S1: Lack of planning”. The Public official and the businessman found the technical barrier “T2: Customs tariff” very influential, and the “T1: Lack of grid” not so influential. Nevertheless, they did not agree on many other preferences. While the public official found “S3: Insecurity related to armed attacks” one of the most influential barriers, the private businessman thought “S2: Bad public-private coordination” was very important.

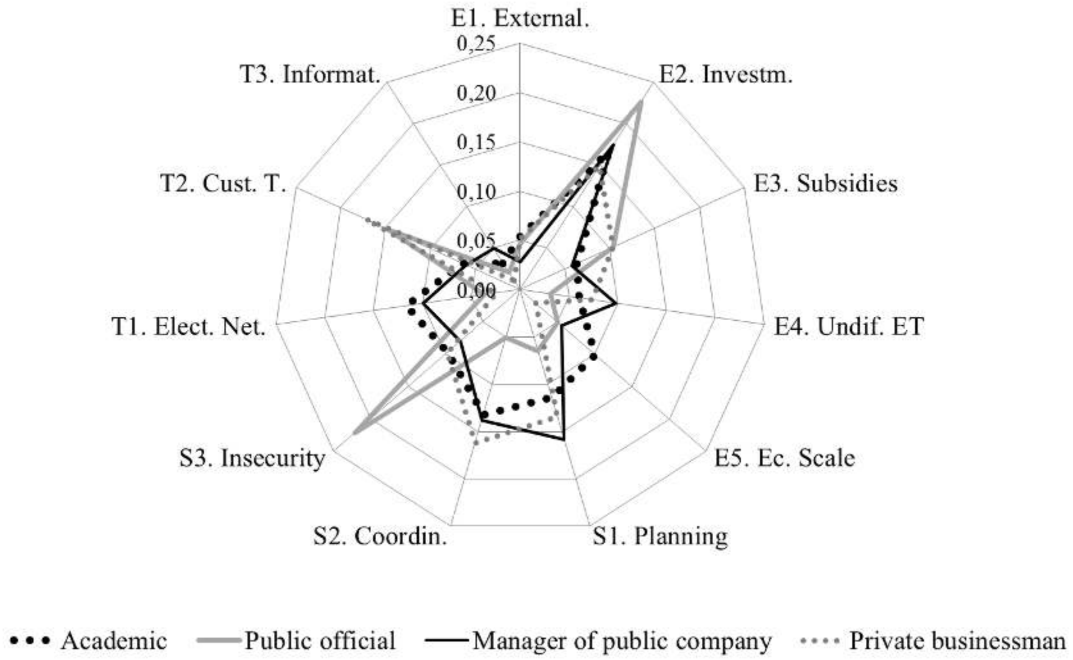

Fig. 7. Results for barriers from each expert.

In FNCE, the academic and the manager agreed on the lower impact amongst small hydro (see Fig. 8). However, the manager showed clear differences about the FNCE, giving more importance to wind power and geothermal power, while the academic showed a very even profile on FNCE. And, to give some other examples, the public official believes that solar PV is the least concerned by barriers, while the private business owner thinks the opposite.

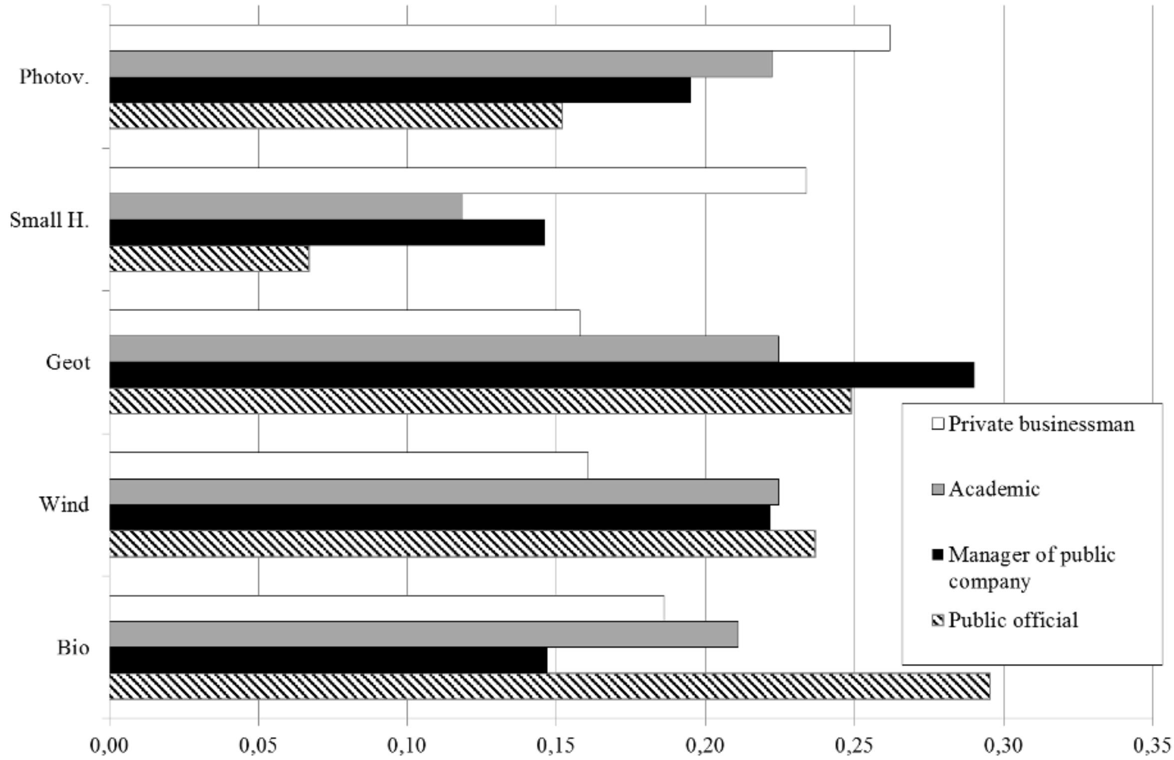

Fig. 8 Results for FNCE per each expert.

Finally, ANP method and Superdecisions® allow the assessing of parts of the full model too. For instance, Fig. 9 includes the partial influence of the obstacles to each FNCE. Aggregated results are displayed in all the charts. Nevertheless, one chart shows the partial contribution of the barriers to wind power according to the academic's judgements. The two charts for wind power are displayed together in order to easily compare the difference between the academic's judgments and those aggregated by the geometric mean. Therefore, ANP helped to understand how much the barriers actually act against each FNCE. Taking the example of small hydro, according to the experts, only a few main obstacles do influence its development in the electricity market. A fact that does not occur with the other FNCE. This detailed analysis has been carried out for every studied element of the model, and each expert's judgements.

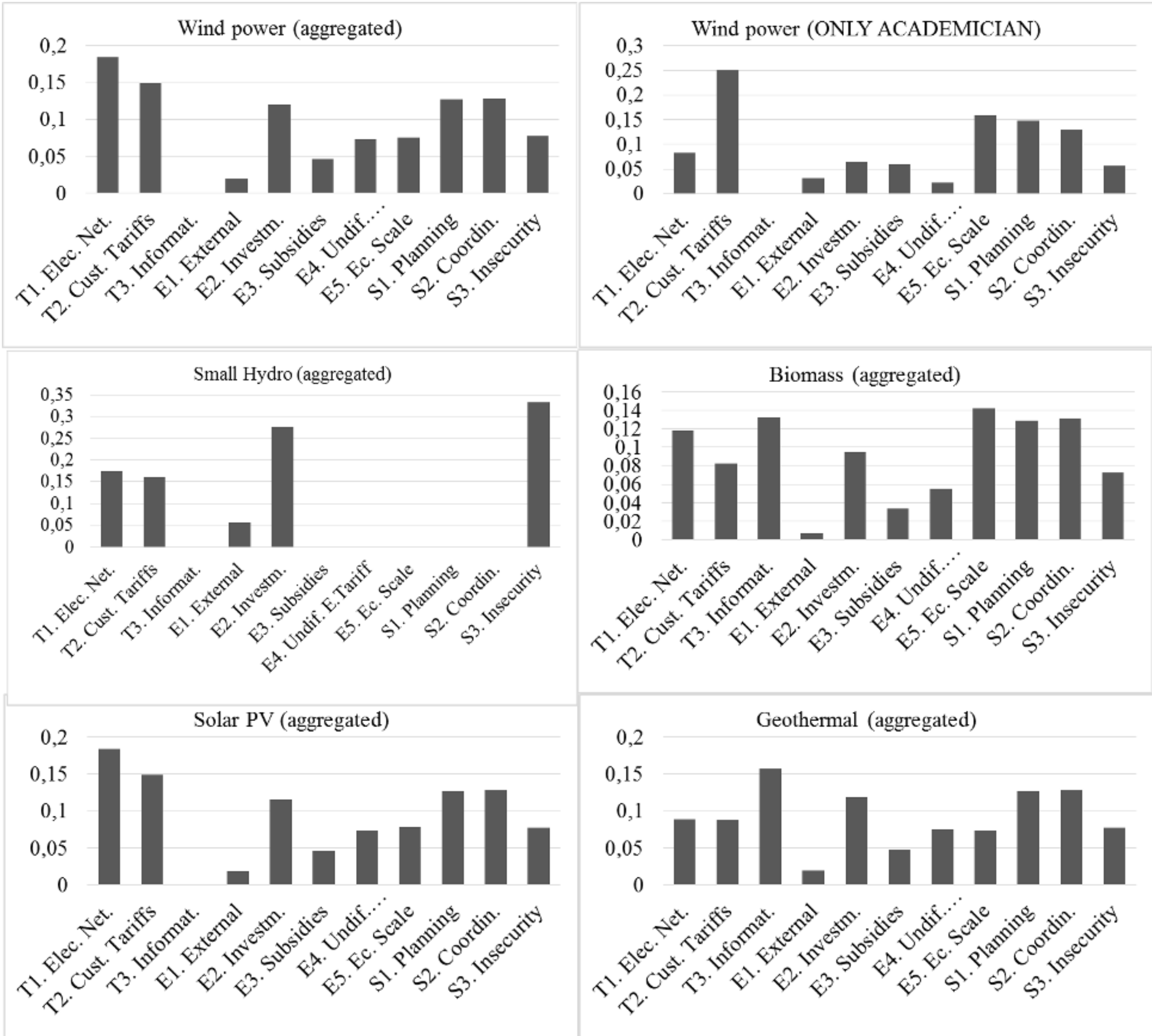

Fig. 9. Partial assessments. Influence of the Barriers in the FNCE.

7. Conclusions

The study hereby presented complements similar studies carried out either in Colombia or in other countries. As a first conclusion, ANP has been successfully implemented to rank barriers and assess their influence on FNCE in Colombia. The followed procedure overcomes research problems related to this case study: incomplete information, qualitative information, uncertain information and disagreement about information. Experts on the topic were consulted about the results and procedure and they showed their satisfaction. They highlighted not only that the results were meaningful and a contribution to the knowledge, but also that the procedure was understandable and obtained as much as possible from the available information.

However, the main limitations of the research are: a) the outcomes show a fixed picture of the situation as barriers, FNCE and their relationships may vary with time, b) experts are needed to deal with the drawbacks of available information, and it is difficult to find them and obtain their help (which is much appreciated for this research), and c) ANP poses certain difficulties to those not familiarised with the tool, and thus the need of ANP facilitators. Finally, disagreement among experts could be a limitation too if a clear, consensualised result is necessary. It is not the case of this study, but in other papers, authors of this research have tackled disagreement applying the Delphi method.

As regards to the results, contrary to other studies, the experts considered that it was not necessary to assess a long list of obstacles. Only a small set of eleven barriers were actually potentially influential. Although there were certain disagreements on each barrier, only six could be included as core obstacles for the development of FNCE. By order of importance they are:

- E2: Start up and operating costs.
- S2: Lack of public and private coordination.
- S1: Lack of FNCE development planning.
- T2: Ineffective exemption of custom tariffs for FNCE equipment
- S3: Insecurity due to the possibility of armed attacks.
- E3: Subsidies to fossil fuels in ZNI

The three first ranked barriers would not be so in an effective market. It has been assumed, based on the literature review and the judgments of the experts (with an exception), that the electric market is not effective for FNCE. If the market was effective, the conclusions would be completely different: FNCE would lack competitive costs compared with conventional energy sources (E2), the market would be fully coordinated through the market rules and different governance bodies (S2), and there would not be a need for further FNCE development planning (S1). Anyhow, the majority of the findings of the research, in parallel with the majority of the conclusions of previous studies, lead to the assumption that the market is not effective yet for FNCE. Hence, public administrations should focus on those obstacles for a more efficient assignment of public resources towards supporting the development of FNCE.

This research has also assessed the relationship between FNCE and the selected barriers for their development. Again, there were differences among the experts, but on average wind power and geothermal power were the most obstructed FNCE. On the other hand, small hydro was deemed, as expected, the most competitive and least concerned with the obstacles. Again, a better assignment of limited public resources can be achieved as the FNCE have also been ranked according to their problems with the barriers.

Furthermore, one of the strengths of the procedure is that the specific influence of the obstacles can be analysed. Something that was not present in the literature. Thus, and as shown in Fig. 9, conclusions can be obtained, such as geothermal power and biomass power needing to overcome the barrier "T3: Insufficient information about the R.E. potential". Or wind power and solar PV are encountering particular problems with the net metering scheme and the connection with the electrical grid (T1).

Finally, as a conclusion of the literature review, the ANP results and the interviews with the experts, some further recommendations can be put forward. They are intended to overcome the barriers and effectively support the contribution of FNCE to the electricity market, mainly in the ZNI. Recommendations regarding the obstacles are (some of them included in law 1715, but not applied yet):

- Switching the investment and generation subsidies in ZNI from diesel generators to FNCE. This action would help FNCE overcome its main barrier: high start up costs. Hence, it will promote a transition to renewable generation, particularly in the ZNI.

- Differentiated tariffs (positive externalities to FNCE) and green taxes. Favourable tariffs for electricity produced by FNCE to balance its higher levelised costs of energy. These rates will transfer positive externalities, such as lower environmental costs, job creation, decentralisation and R&D promotion. Besides, green taxes could be an income for supporting FNCE lower taxes.
- Green purchasing. Public electricity demand can help make the electricity produced by renewable energies competitive.
- Establishment of an FNCE programme. Long term electricity capacity planning promoting FNCE will incentivate national and international investment. In order to do so, the engagement of all stakeholders is necessary. There should be a procedure for participation where needs and experiences from the public and private sectors can be usefully shared. Furthermore, it would foster trust between stakeholders.
- Effective exemption of custom tariffs. Improve the personnel training and procedures to assign tariff reductions to FNCE imported equipment.
- Successful peace agreements. The end of the military conflict will probably help the development of all FNCE in the ZNI.
- R&D plans to promote FNCE. Promoting collaboration between universities, research centres and private companies could lead to the development of renewable hybrid power stations. Afterwards, hybrid generation could totally replace diesel generators in ZNI.

Recommendations regarding the FNCE, added to the above mentioned are:

- For Wind power.
  - Promotion of electricity grid in ZNI associated with FNCE. That recommendation would help all FNCE, but according to the experts, it is particularly necessary for wind power projects, normally intended to produce a surplus of energy to be sold.
- For Geothermal power:
  - Updates and more detailed Geographical information systems (GIS) about the potential of FNCE, particularly Geothermal and Biomass power.
- For Solar PV power:
  - Promotion of electricity grid in ZNI associated with FNCE. In this case, the grid would both help by selling the energy surplus, or provide electricity when the PV system can not cover the demand.
  - Self-consumption law. Modify the law for self-consumption with a positive balance, economically supporting the selling of the surplus electricity. Although something similar is included in law 1715/2014, the trade of surplus from self-generation should be helped to be viable both in ZNI and SIN. Currently, as far as the authors know, very little has been done and [1] suggests it would only be viable in stratums 5 and 6, i.e. the Colombian upper class neighbourhoods.

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