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Gómez-Navarro, T.; Ribó-Pérez, DG. (2018). Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia. *Renewable and Sustainable Energy Reviews*. 90:131-141. <https://doi.org/10.1016/j.rser.2018.03.015>



The final publication is available at

<https://doi.org/10.1016/j.rser.2018.03.015>

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Additional Information

# 1 **Assessing the obstacles to the participation of renewable energy sources in the** 2 **electricity market of Colombia.**

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

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

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

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

## 21 **1. Introduction**

22 Colombia is one of the main emerging economies of the South American continent with an ever  
23 growing energy demand. Electricity consumption is not only increasing but also changing from a  
24 matrix almost completely based on Hydropower, to a mix, where fossil fuels are ever more prevalent  
25 [1]. Furthermore, there is a large portion of the country's surface where electricity distribution cannot  
26 reach consumption, and diesel engines are mostly providing the demanded electricity supply.

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

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

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

### 39 **1.1. Energy market in Colombia**

#### 40 *1.1.1. Energy demand and mix.*

41 According to the UPME (Mining and Power Planning Unit), Colombian primary energy consumption  
42 has increased more than 200% in the past 3 decades. As a matter of fact, it has increased from  
43 205,150 GWh in 1980 to 454,260 GWh in 2012 [1] (last available data). However, the final energy

44 consumption per unit of GDP has declined by 50% during this period. Hence, the country has made  
45 a noticeable effort in implementing energy efficiency measures while increasing its primary energy  
46 consumption.

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

#### 50 1.1.2. *Electrical energy mix*

51 The Colombian electricity sector has a constantly evolving regulatory framework. Currently,  
52 generation and supply work under open market competition, while transmission and distribution  
53 remain as regulated monopolies [3]. Electricity consumption in 1975 was 11,275 GWh while during  
54 2012 this consumption rose to 59,988 GWh. This represents an increase of more than 500% in 37  
55 years [1]. The Colombian electricity mix is dominated by hydroelectric production, which used to  
56 represent around 80% until recently.

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

#### 63 1.1.3. *Interconnected systems and non-interconnected zones.*

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

#### 70 1.1.4. *Law 1715 for the integration of FNCE in the national energy system.*

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

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

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

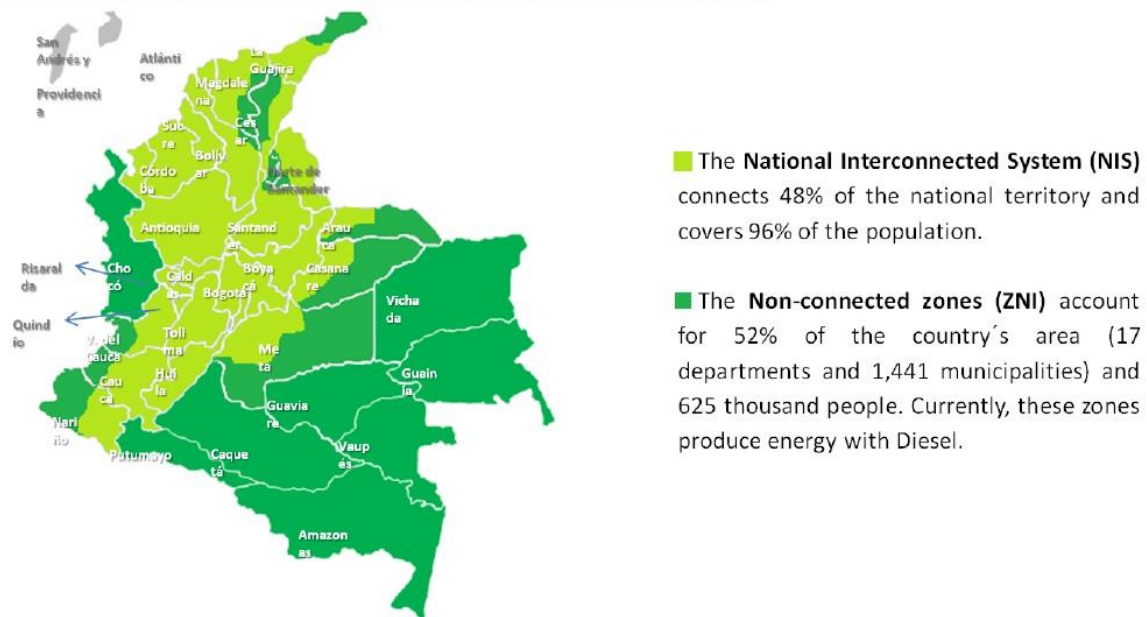
- 85 • There is a lack of regulations for self-generation, sales of self-generated electricity and the
- 86 maximum capacities for FNCE projects.

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

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

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

### Connected and Non-connected Zones in Colombia



98  
 99 Fig. 1. ZNI and SIN (NIS) in Colombia [1].

## 100 2. Renewable energy sources

101 This chapter presents the FNCE with greater potential to penetrate in the Colombian electricity  
 102 market. solar photovoltaic, wind, biomass (including solid waste), small hydroelectric and geothermal  
 103 were chosen according to the literature review and with the agreement of the consulted experts  
 104 [1,7,12,13]. On the other hand, solar thermal power does not contribute to the electricity market and  
 105 is not supported by the authorities [1]. Tide and wave power and ocean thermal energy, although  
 106 creating a growth of interest in Colombia, are neither present nowadays nor are there envisaged  
 107 projects in the short term, despite their potential [1,14,15].

### 108 2.1. Wind power

109 The net installed wind generation capacity is 19.5 MW (2013) in only one power plant, which equals  
 110 0.1% of the country's total net generation capacity. Between 2010 and 2014, wind power produced  
 111 an average of 52.2 GWh per year [3]. According to [1,15], wind energy potential could be converted  
 112 into an installed capacity of up to 25 GW.

113 **2.2. Solar Photovoltaic**

114 Colombia has a high potential for solar energy and relevant opportunities because solar radiation  
115 throughout the country is mostly uniform during the year (average 4.5 KWh/m<sup>2</sup>/day). However,  
116 estimations made by [5,7], showed that the installed Colombian solar capacity was around 9 MWp by  
117 2010. All of this capacity corresponded to private systems, business applications and solutions in  
118 ZNI (mostly formed by low capacity photovoltaic systems of less than 10 kWp). Estimations of the  
119 potential installable capacity for solar photovoltaic power were not found, but [16] analyses the solar  
120 radiation potential in some Colombian regions, although most of them are in the SIN area (see Fig.  
121 1). Moreover, the steady decrease in capital costs and the advantageous equatorial situation have  
122 increased the interest for PV in Colombia. For instance, [7] have studied support schemes to promote  
123 the development of this technology in urban areas.

124 **2.3. Biomass**

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

129 **2.4. Geothermal**

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

134 **2.5. Small Hydroelectric plants**

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

141 According to [5], small hydroelectric power has an estimated potential of 25 GW installed. Small hydro  
142 is the most competitive FNCE due to its early paybacks and reliable technology among other reasons.  
143 Thus, it is the most developed FNCE in both SIN and ZNI. Currently the installed capacity has reached  
144 784.44 MW [1,18,19] in more than 200 plants (and many others non-connected to the grid), and there  
145 are various ongoing projects for increasing this amount.

146 **3. Obstacles to FNCE development.**

147 Colombia has an electricity matrix with a big renewable energy share because of hydropower. If other  
148 renewables were promoted, Colombia could almost reach 100% renewable electricity production  
149 [1,15]. However, despite the existing support programs and the announced ones, FNCE are almost  
150 testimonial in the electricity market. To identify the barriers preventing the development of FNCE, an  
151 extensive literature review was conducted. This literature review, and the following discussion of its  
152 outcomes with four experts, were part of the research methodology as will be explained in section 5.  
153 Nevertheless, the main findings are advanced here in order to explain how the obstacles to FNCE  
154 development were identified.

155 Of the several published research works found, the most helpful six have been summarized in table  
156 1 (for a complete review of barriers to decentralized renewable energy systems see [20]). As can be

157 seen, the countries under study were as diverse as China, Tanzania or UK. In any case, meaningful  
 158 similarities were found. Those papers, together with others like [5,11,12] help to suggest a starting list  
 159 of obstacles and a set of relationships with the list of renewable energy technologies. In the following  
 160 sections, these starting lists are discussed and adapted to the case study.

161 Table 1.

162 Main findings in the literature review.

<b>Research</b>	<b>Country and Barriers found.</b>	<b>Renewable energy technologies</b>	<b>Method</b>
[21]	Turkey. <ul style="list-style-type: none"> <li>• Lack of knowledge               <ul style="list-style-type: none"> <li>– Policy-makers</li> <li>– Potential consumers</li> <li>– Energy firms</li> </ul> </li> <li>• Economic</li> <li>• Market culture</li> </ul>	<ul style="list-style-type: none"> <li>• Wind power</li> <li>• Hydropower</li> <li>• Biogas and biomass power,</li> <li>• Geothermal power,</li> <li>• Solar thermal power</li> <li>• Solar electricity power</li> </ul>	Literature review and research on topic reports
[22]	India. 28 barriers grouped in 7 dimensions: <ul style="list-style-type: none"> <li>• Economic and financial</li> <li>• Market</li> <li>• Awareness and information</li> <li>• Technical</li> <li>• Ecological and geographical</li> <li>• Cultural and behavioural</li> <li>• Political and government Issues</li> </ul>	<ul style="list-style-type: none"> <li>• Solar energy</li> <li>• Wind energy</li> <li>• Hydro energy</li> <li>• Geothermal energy</li> <li>• Biomass energy</li> <li>• Tidal power</li> <li>• Wave power</li> </ul>	Analytical Hierarchy Process (AHP)
[23]	China. <ul style="list-style-type: none"> <li>• The unbalanced development of regional economy</li> <li>• The scale barrier of renewable industry</li> <li>• The lagged construction of power grid</li> <li>• The lack of market base.</li> <li>• The inadequate incentive and supervision mechanisms</li> </ul>	<ul style="list-style-type: none"> <li>• Solar energy</li> <li>• Wind power</li> <li>• Hydro energy</li> <li>• Geothermal energy</li> <li>• Biomass energy</li> </ul>	Literature review and research on topic reports
[24]	Mainly Canada, also UK and Denmark. 22 barriers grouped in 4 clusters: <ul style="list-style-type: none"> <li>• Financial and legal hindrances</li> <li>• Physical hindrances</li> <li>• Ontological and social hindrances</li> <li>• Technological hindrances</li> </ul>	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: <ul style="list-style-type: none"> <li>• Weak institutions and organizations</li> <li>• Economic finance</li> </ul>	Not specified	Literature review and interviews

	<ul style="list-style-type: none"> <li>• Social dimensions</li> <li>• Technological system and local management</li> <li>• Technology diffusion and adaptation</li> <li>• Rural infrastructure</li> </ul>		
[26]	<p>Australia.</p> <ul style="list-style-type: none"> <li>• Administrative hurdles</li> <li>• Problems for grid connection</li> <li>• Policy instability</li> <li>• Lack of social acceptance</li> <li>• Cost competitiveness</li> <li>• Govern support to conventional sources of energy.</li> </ul>	Not specified	Literature review and research on topic reports
[1]	<p>Colombia.</p> <ul style="list-style-type: none"> <li>• Subsidies for conventional sources.</li> <li>• High costs and financing difficulties.</li> <li>• Market barriers.</li> <li>• Scale economies.</li> <li>• Externalities</li> <li>• Lack of information</li> <li>• Lack of human capital</li> <li>• Technological prejudice,</li> <li>• Higher transaction costs</li> <li>• Regulatory and institutional factors</li> </ul>	<ul style="list-style-type: none"> <li>• Solar energy</li> <li>• Wind power</li> <li>• Geothermal Energy</li> <li>• Biomass energy</li> </ul>	Literature review and research on topic reports

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

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

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

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

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

### 190 **3.1. CLUSTER 1: Technical barriers**

#### 191 3.1.1. *T1: Lack of electric grid in non interconnected zones (ZNI):*

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

#### 197 3.1.2. *T2: Customs tariff:*

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

#### 202 3.1.3. *T3: Insufficient information about the potential of renewable energy sources:*

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

### 206 **3.2. CLUSTER 2: Economic barriers**

#### 207 3.2.1. *E1: Externalities:*

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

#### 212 3.2.2. *E2: Investment and operating costs (Levelised cost of electricity: LCOE):*

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

#### 218 3.2.3. *E3: Fossil fuels subsidy:*

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

#### 223 3.2.4. *E4: Undifferentiated electricity tariffs:*

224 The electricity price is determined by the spot market. Thus, every MWh is paid at the same price  
225 regardless of the type of generating technology or the geographical location. Consequently, electricity



226 production tariffs are economically insufficient for developing technologies since FNCE have to  
227 compete on equal terms with conventional energy technologies such as coal, gas and hydropower.  
228 That is why, generally, renewable energy development plans include initial subsidies to production  
229 with FNCE [1,32].

#### 230 3.2.5. *E5: Economies of scale:*

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

### 234 **3.3. CLUSTER 3: Social barriers**

#### 235 3.3.1. *S1: Lack of planning:*

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

#### 241 3.3.2. *S2: Bad public-private coordination:*

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

#### 247 3.3.3. *S3: Insecurity related to armed attacks:*

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

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

## 255 **4. Analytical Network Process methodology.**

### 256 **4.1. The method.**

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

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

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

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

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

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

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

$$286 \quad A = \begin{pmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{pmatrix} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \quad (1)$$

287 After all pairwise comparisons are completed and the consistency of the matrix has been checked  
 288 [28], the priority weighting vector ( $W$ ) is computed as the principal eigenvector of the pairwise  
 289 comparisons matrix.

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

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

293 (iii) Constructing the weighted supermatrix.

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

296 (iv) Calculation of the global priority weightings.

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

300 (v) Interpretation of the results.

301 The priority of each criterion (barrier) is a non-dimensional value. Based on the answers to the  
 302 questions made to the experts, it will consider the influence of the barrier on the other barriers and on  
 303 the alternatives. The higher the value, the more influential the barrier. Similarly, the non-dimensional  
 304 values obtained for the FNCE represent how much they interact with other elements in the model,

305 that is to say, how much they are affected by the barriers. Afterwards, the methodology based on  
306 ANP is explained, together with the case study.

## 307 **5. Methodology and case study.**

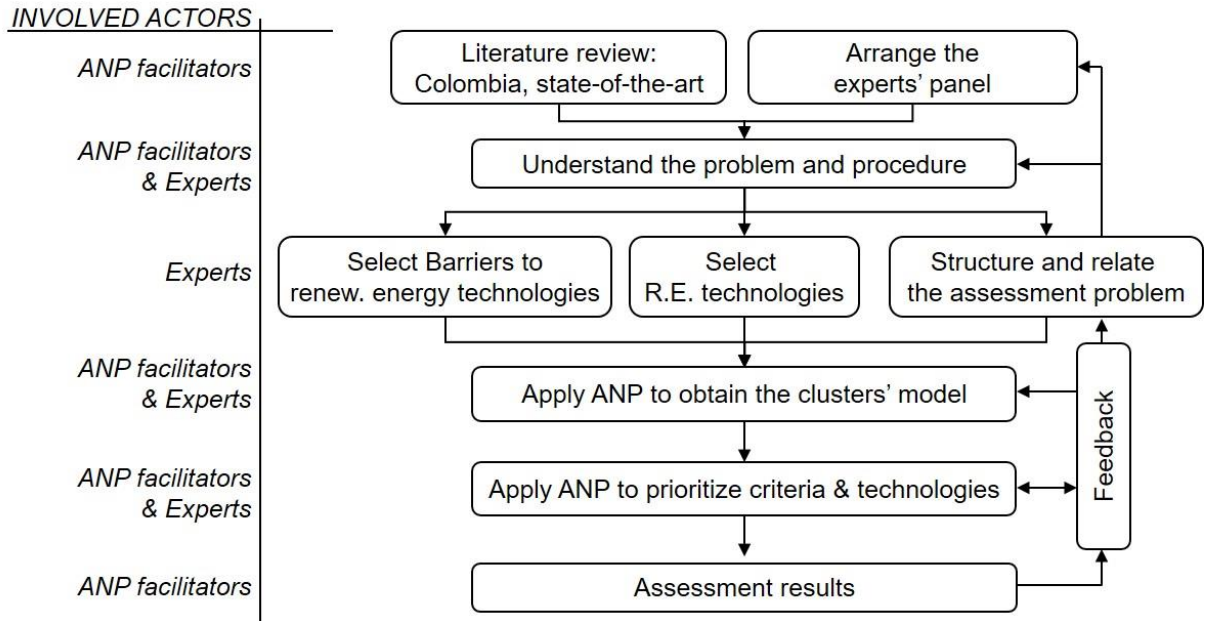
### 308 **5.1. Description of the Evaluation Process**

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

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

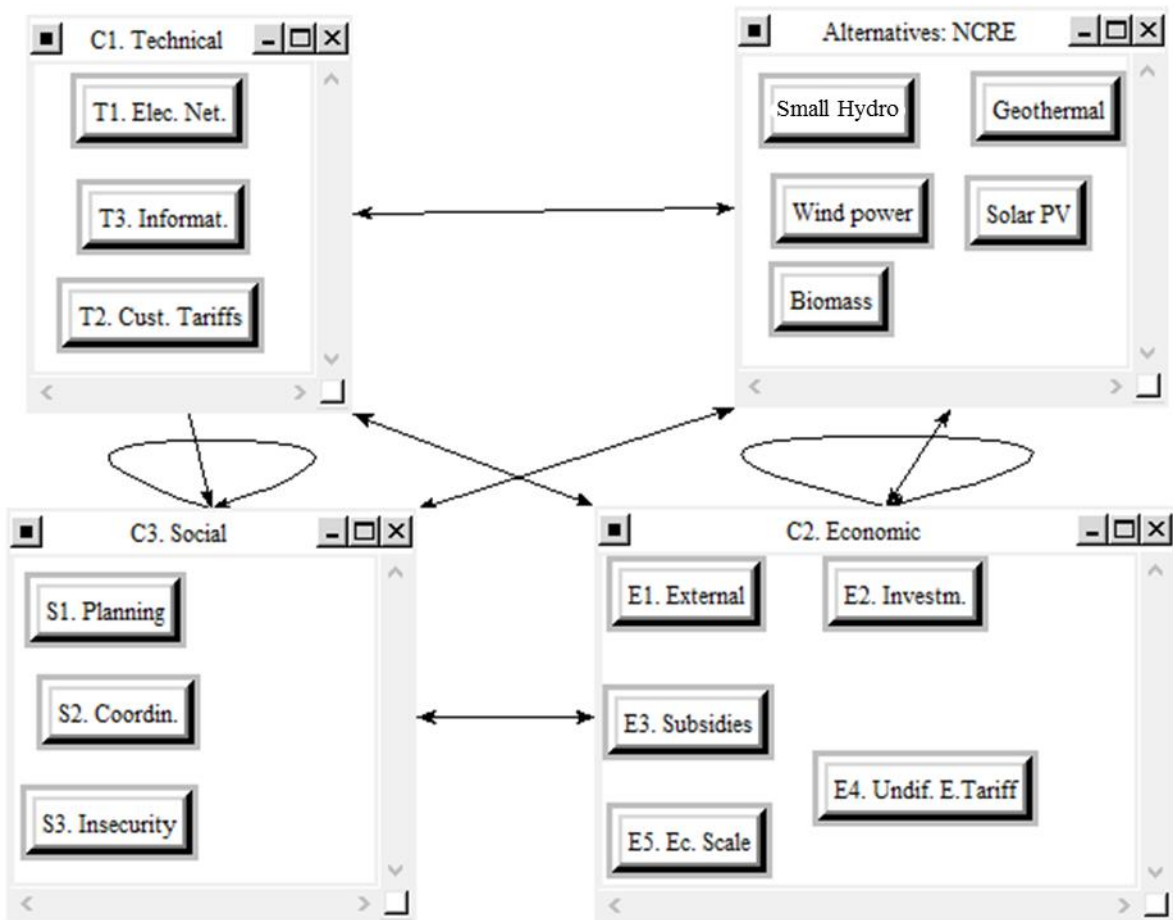
331 In ANP, due to the kind of information available, the quality of experts is more important than the  
332 number of them, as discussed in [24]. To be considered an appropriate expert for the research,  
333 requisites are: broad experience on the issue, personal research on the issue (demonstrable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

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



342

343 Fig. 2. Assessment procedure.



344

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

346 The first stage of the methodology was the literature review (advanced in section 3) and the  
 347 arrangement of the experts' panel (explained in section 5.1.). After that, several meetings were held

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

356 In the next step of the procedure each expert went through an interview based on a questionnaire.  
 357 The questionnaire required respondents to: (i) compare clusters against clusters; (ii) compare criteria  
 358 against criteria; (iii) analyze each alternative against the barriers under study; and (iv) compare  
 359 alternatives with alternatives (see example of its questions in Fig. 4). Answers to the questions were  
 360 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?	<input type="checkbox"/> A2	<input checked="" type="checkbox"/> A3			
How much?	<input type="checkbox"/> Equal	<input type="checkbox"/> Moderately	<input checked="" type="checkbox"/> Strongly	<input type="checkbox"/> Very strongly	<input type="checkbox"/> Extreme

361

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

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

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

371 **6. Discussion of results.**

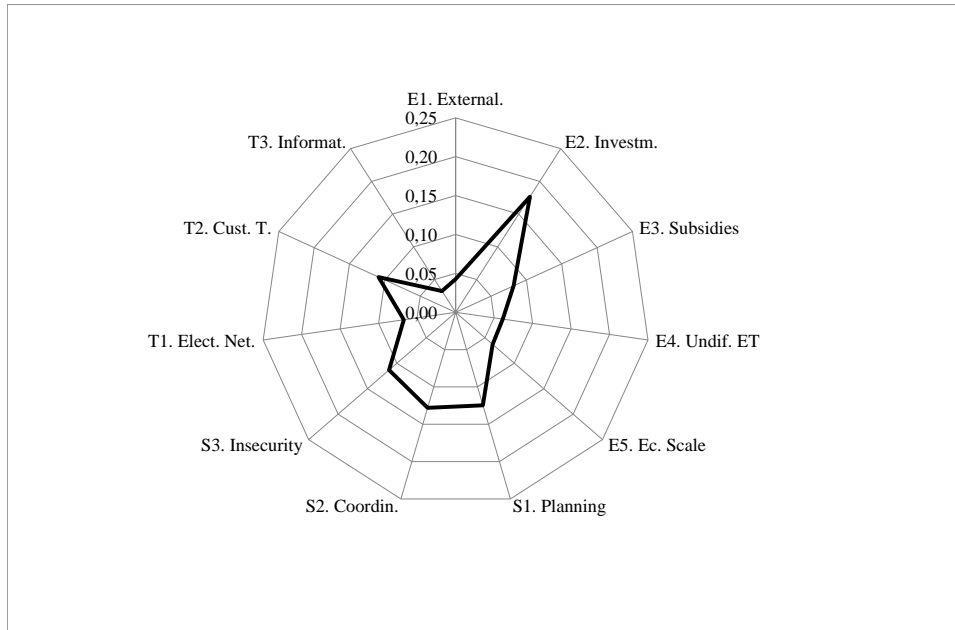
372 The limit supermatrix, normalized for each expert, was computed according to the ANP methodology.  
 373 Table 2 shows the results for each expert and the aggregated (geometric mean). Note that the values  
 374 were normalized in two general groups: Barriers and FNCE. Fig. 5, 6, 7 and 8 show results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

377 Table 2.

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

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

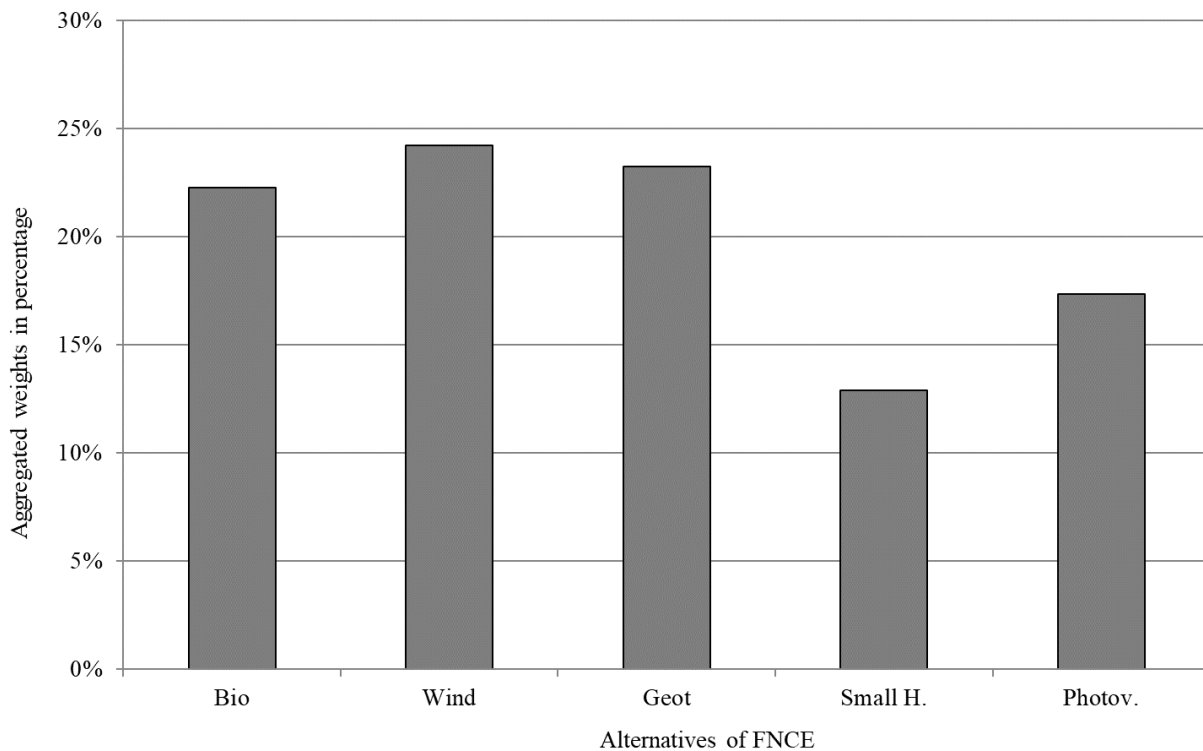
388 Aggregated results show, as expected, the economic barrier “E2: Costs of investment and operating”  
389 is the most influential (see Fig. 5). All experts agreed on that, and agreed on giving relatively little  
390 importance to the other economic obstacles. Social obstacles were found to be very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



395

396 Fig. 5. Aggregated results for barriers.

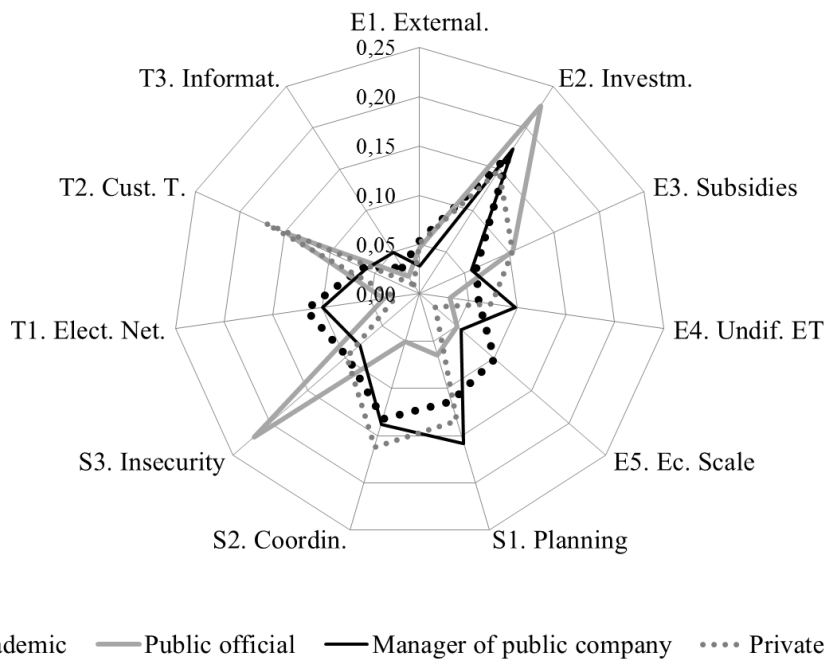
397 About FNCE, unexpectedly, wind power was deemed as the most influenced by the barriers, along  
 398 with the geothermal one (see Fig. 6). When experts were asked about it, they found the result  
 399 understandable. However, there were different reasons for the results. As shown in Fig. 9, Wind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



404

405 Fig. 6. Aggregated results for FNCE.

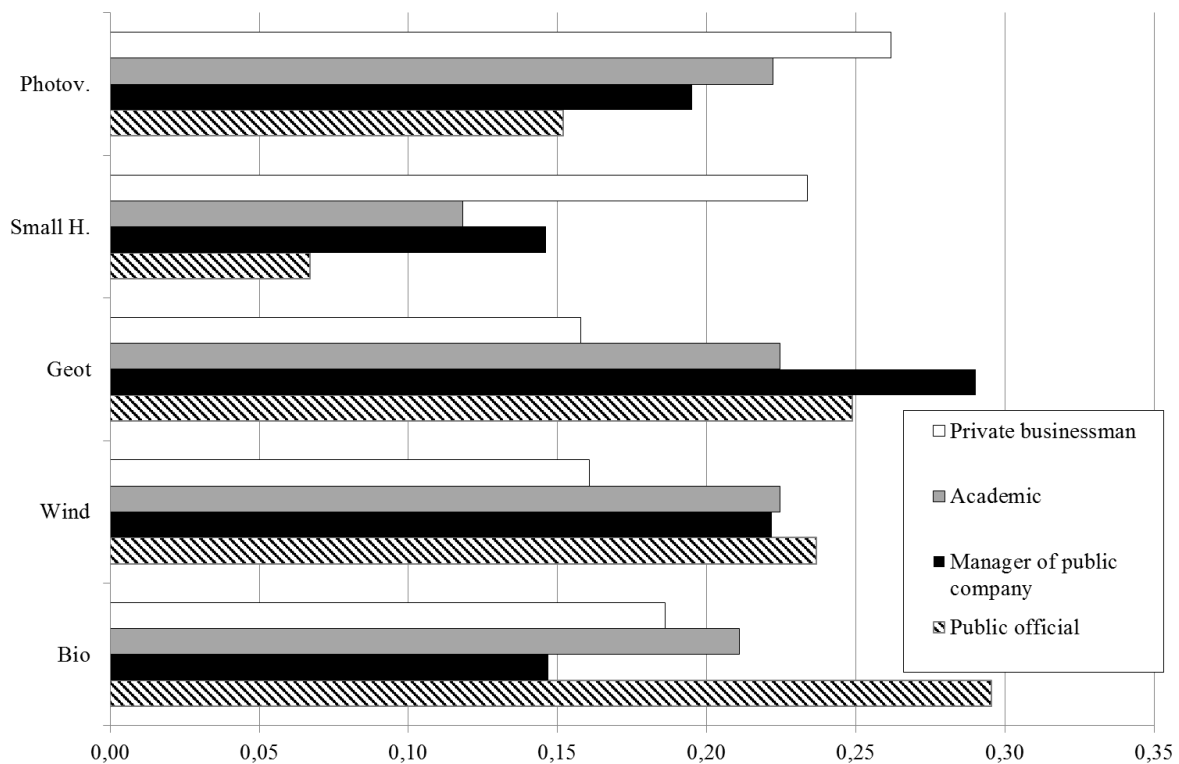
406 Separated results per expert show how the Manager of a public company and the academic obtained  
 407 a similar profile regarding the barriers, except for the social cluster (see Fig. 8). The academic showed  
 408 a preference for obstacles: “E2: Costs”, “T1: Lack of grid” and “S2: Bad coordination”,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



414  
 415 Fig. 7. Results for barriers from each expert.

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

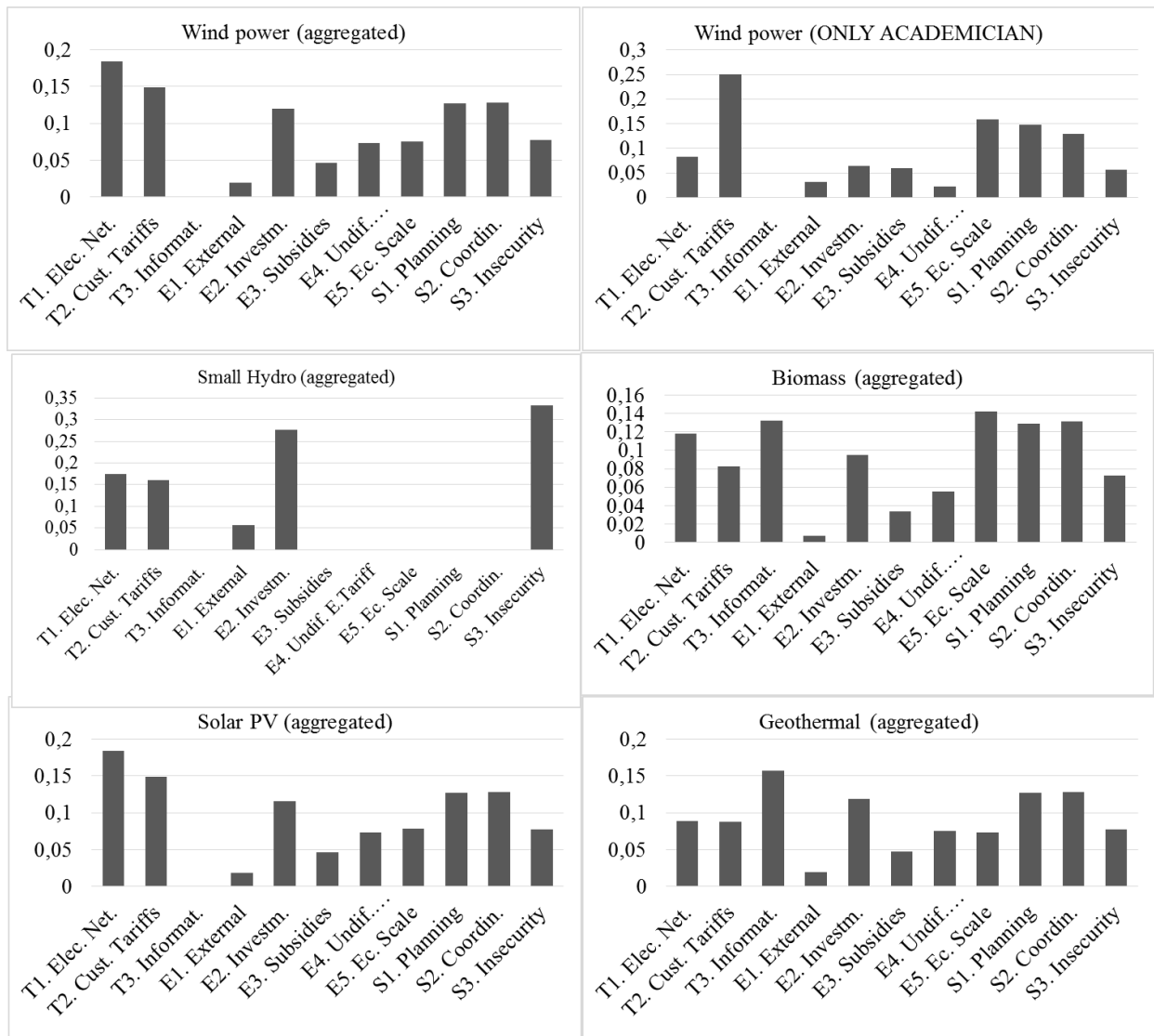




421

422 Fig. 8 Results for FNCE per each expert.

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



433  
434 Fig. 9. Partial assessments. Influence of the Barriers in the FNCE.

435 **7. Conclusions**

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

444 However, the main limitations of the research are: a) the outcomes show a fixed picture of the situation  
 445 as barriers, FNCE and their relationships may vary with time, b) experts are needed to deal with the  
 446 drawbacks of available information, and it is difficult to find them and obtain their help (which is much  
 447 appreciated for this research), and c) ANP poses certain difficulties to those not familiarised with the  
 448 tool, and thus the need of ANP facilitators. Finally, disagreement among experts could be a limitation

449 too if a clear, consensualised result is necessary. It is not the case of this study, but in other papers,  
450 authors of this research have tackled disagreement applying the Delphi method.

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

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

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

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

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

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

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

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

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

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

## 529 Acknowledgements

530 We do appreciate the help of our four experts in the field. Without them, it would not have been  
531 possible to carry out the research. Besides, we are grateful to the reviewers for their comments and  
532 suggestions, which helped in the improvement of the manuscript.

533 This research did not receive any specific grant from funding agencies in the public, commercial, or  
534 non-profit making sectors.

535

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