Assessing and optimising the sustainability objective of electricity generation systems, and energy systems of special interest to Galicia

Author: Juan José Cartelle Barros

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Advisors: Alfredo del Caño Gochi. Manuel Lara Coira.

Tutor: Manuel Lara Coira

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UNIVERSIDADE DA CORUÑA

D. Alfredo del Caño Gochi, Catedrático de Universidad del Departamento de Ingeniería Civil de la *Universidade da Coruña* y,

D. Manuel Lara Coira, Profesor Contratado Doctor del Departamento de Ciencias de la Navegación e Ingeniería Marina de la *Universidade da Coruña*,

CERTIFICAN QUE LA MEMORIA TITULADA:

“Assessing and optimising the sustainability objective of electricity generation systems, and energy systems of special interest to Galicia”

“Avaliación e optimización do obxectivo de sustentabilidade en centrais de produción de electricidade, e en sistemas enerxéticos de especial interese para Galicia”

“Evaluación y optimización del objetivo de sostenibilidad en centrales de producción de electricidad, y en sistemas energéticos de especial interés para Galicia”

ha sido realizada por **D. Juan José Cartelle Barros** bajo nuestra dirección, y constituye la Tesis que presenta para conseguir el grado de Doctor. Esta memoria opta a la Mención Internacional y será presentada como un compendio de publicaciones.

Fdo. Alfredo del Caño Gochi

Fdo. Manuel Lara Coira

Fdo. Juan José Cartelle Barros

A mi familia

En recuerdo de Maica

To my family

In loving memory of Maica

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Abstract

In recent years, a considerable number of authors have carried out studies addressing the sustainability assessment of both renewable and non-renewable power plants. Despite this, there are still methodological and scope limitations that impede public and private companies, authorities responsible for energy planning, as well as the wider public, clearly and precisely understand the real economic, social and environmental impacts associated with the electricity production, throughout its life cycle. On the other hand, it is now necessary to go further the assessment, looking for the optimisation, in the sense of maximising the contribution to sustainable development of energy and other complex systems. Nevertheless, sustainability optimisation is at an early stage. In fact, until the present, it has received much less attention than the assessment.

This work aims to cover the gaps in the current knowledge with respect to the sustainability assessment of power plants. Furthermore, it addresses the sustainability optimisation of a shell and tube heat exchanger, as a first step to optimise more complex energy systems.

Resumo

Nos últimos anos, unha cantidade considerable de autores levaron a cabo estudos que abordan a avaliación da sustentabilidade de centrais eléctricas tanto renovables coma non renovables. A pesar diso, seguen existindo unha serie de limitacións de tipo metodolóxico e de alcance que impiden ás empresas, tanto públicas coma privadas, ás autoridades responsables da planificación enerxética, así coma ao público xeral, comprender de forma clara e precisa cales son os verdadeiros impactos económicos, sociais e medioambientais derivados da produción de enerxía eléctrica, ao longo do seu ciclo de vida. Por outra banda, é preciso ir máis alá da mera avaliación, buscando a optimización, no sentido de maximizar a contribución ao desenvolvemento sustentable de sistemas complexos, entre eles os enerxéticos. Con todo, a optimización da sustentabilidade atópase nunha fase inicial, recibindo, ata o momento, moita menos atención que a avaliación.

Este traballo pretende cubrir as lagoas existentes en materia de avaliación da sustentabilidade de centrais eléctricas. Ademais, aborda a optimización da sustentabilidade dun intercambiador de calor de carcasa e tubos, como primeiro paso á optimización da sustentabilidade de sistemas enerxéticos mais complexos.

Resumen

En los últimos años, una cantidad considerable de autores han llevado a cabo estudios que abordan la evaluación de la sostenibilidad de centrales eléctricas, tanto renovables como no renovables. Pese a ello, siguen existiendo una serie de limitaciones de tipo metodológico y de alcance que impiden a las empresas, tanto públicas como privadas, a las autoridades responsables de la planificación energética, así como al público general, comprender de forma clara y precisa cuales son los verdaderos impactos económicos, sociales y medioambientales derivados de la producción de energía eléctrica, a lo largo de su ciclo de vida. Por otro lado, es necesario ir más allá de la mera evaluación, buscando la optimización, en el sentido de maximizar la contribución al desarrollo sostenible de sistemas complejos, entre ellos los energéticos. Sin embargo, la optimización de la sostenibilidad se encuentra en una fase inicial, habiendo recibido, hasta el momento, mucha menos atención que la evaluación.

Este trabajo pretende cubrir las lagunas existentes en materia de evaluación de la sostenibilidad de centrales eléctricas. Además, aborda la optimización de la sostenibilidad de un intercambiador de calor de carcasa y tubos, como un primer paso hacia la optimización de sistemas energéticos más complejos.

Fulfilment of scientific requirements

This Doctoral Thesis meets the traditional scientific requirements for research studies (García, 1994):

- It deals with a specific, recognizable and identifiable matter.
- As far as can be known, after an extensive literature review, the issues addressed in this Thesis were not previously studied in the same way that is done here. Therefore, this work makes original contributions, described in detail in the introduction section.
- The essential data for the verification or refutation of hypotheses and results are included in this document.
- Regarding the sustainability assessment, among other recipients, this thesis can be of interest to:
    - Researchers.
    - Public and private companies in the energy sector.
    - Authorities responsible for the regional, national or transnational energy planning.
    - Large-electricity consuming companies, which pursue a more sustainable consumption pattern.
    - Non-governmental organisations.
    - And, in general, to many people of the wider public who ask themselves about the subjects discussed here, all over the world.
    - In fact, it is hoped that advances made with the models presented in this thesis make it easier to analyse the various impacts of electricity production in greater depth. Therefore, public and private decision makers will be able to work with greater objectivity. Some of the results can also influence the policies related to financial subsidies for renewables.
    - With regard to Galicia, the results can be useful in the strategic and political areas as the basis for the diversification of the Galician energy sector, promoting those alternatives of interest with high levels of contribution to sustainable development.
- Regarding the sustainability optimisation, among other recipients, this thesis can be of interest to researchers, engineers and manufacturers of engineering systems, in particular energy systems and, more specifically, heat exchangers.

Publications resulting from this Thesis

During the development of this doctoral work, the following publications have been made:

de la Cruz, M.P., Castro, A., del Caño, A., Gómez, D., Lara, M., **Cartelle, J.**, 2014. Comprehensive methods for dealing with uncertainty in assessing sustainability. Part I: the MIVES-Monte Carlo method, in: García-Cascales, M.S., Sánchez-Lozano, J.M., Masegosa, A.D., Cruz-Corona, C. (Eds.), Soft computing applications for renewable energy and energy efficiency. IGI Global, Hershey, pp. 69-106.

Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2015. Assessing the global sustainability of different electricity generation systems. Energy 89, 473-489. doi:10.1016/j.energy.2015.05.110.

Cartelle, J.J., Lara, M., de la Cruz, M.P., del Caño, A., 2015. Indicators for assessing sustainability of power plants: environmental, social, economic and technical aspects. International Conference on Renewable Energies and Power Quality (ICREPQ'2015).

del Caño, A., de la Cruz, M.P., **Cartelle, J.J.**, Lara, M., 2015. Conceptual framework for an integrated method to optimise sustainability of engineering systems. International Conference on Renewable Energies and Power Quality (ICREPQ'2015). After some modifications and improvements, this paper was also published in the Journal of Energy and Power Engineering.

del Caño, A., de la Cruz, M.P., **Cartelle, J.J.**, Lara, M., 2015. Conceptual framework for an integrated method to optimize sustainability of engineering systems. Journal of Energy and Power Engineering. 9, 608-615. doi:10.17265/1934-8975/2015.07.002.

Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2015. Probabilistic assessment of the life-cycle costs of renewable and non-renewable power plants. International Congress on Project Management and Engineering, 171-184.

Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2016. Probabilistic life-cycle cost analysis for renewable and non-renewable power plants. Energy 112, 774–787. doi:10.1016/j.energy.2016.06.098.

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Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2017. Comparative analysis of direct employment generated by renewable and non-renewable power plants. Energy 9, 147–166. doi:10.1016/j.energy.2017.08.025.

Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2018. Sustainability optimisation of shell and tube heat exchanger, using a new integrated methodology. Submitted to the Journal of Cleaner Production on 26 December 2017. It is currently under review.

In order to facilitate the reading and comprehension of this Thesis, only the original articles published (or under review) in JCR journals were included in Appendix A.

List of abbreviations

AHP	Analytic hierarchy process
BCR	Benefit to cost ratio
EI	Economic index
ENI	Environmental index
IO	Input-output
IRR	Internal rate of return
LCOE	Levelised cost of electricity
MIVES	*Modelo Integrado de Valor para una Evaluación sostenible* (or Integrated Value Model for Sustainability Assessment, in translation)
NIMBY	Not in my back yard
NPV	Net present value
NSGA	Non-dominated sorting genetic algorithm
NSGA-II	Non-dominated sorting genetic algorithm II
PBP	Pay back period
SI	Sustainability index
SOI	Social index
STHE	Shell and tube heat exchanger
UK	United Kingdom

Content

Introduction

1. Background and motivation

Nowadays, it is accepted that there are limits on growth (Meadows et al., 2004) and development. In fact, neither the Earth's ecosystems nor the world population and its communities will withstand the impact made by human activity if the current trend of growth is maintained over the years (Bouvier and Grant, 1994). Due to this, measures are starting to be taken to protect existing and future populations from the consequences of overcoming those limits.

As a result, integral sustainability (United Nations, 1992) and sustainable development (United Nations, 1987) are two terms that have acquired a great relevance in almost any sphere of activity, including, among others, the economy and the industry and, particularly, the construction and energy sectors. These two terms go beyond environmental aspects, including social, economic and technical issues.

On the other hand, government planners face the challenge of ensuring that the necessary conditions for a country to develop are met. In this context, energy plays a crucial role not only in every nation's industrialisation but also in its social development (Fröling, 2011; Wilson et al., 2013), since it facilitates life through lighting, heating and transport (Çetin and Egrican, 2011). Therefore, at the heart of every nation's energy system should be abundant and high quality resources, obtained at a cost-efficient price and easily transported, that ensure a constant supply.

It is indispensable to note that the ideal (efficient, cost-effective, risk-free and environmentally friendly) energy system does not exist today. Consequently, all types of power plants present economic, social, environmental and technical issues to be analysed, challenges to be addressed and risks to be assessed (Vujic et al., 2012).

In other words, there is a growing need to assess the integral sustainability of renewable and non-renewable power plants throughout their life cycles. This would make society and decision makers more aware of the impacts associated with the electricity industry's processing chain.

In the current context of economic and financial crisis, there are two crucial elements to sustainability that have reached a critical importance: the costs and the employment generation.

Regarding the former aspect, it is a widely accepted fact that the economics of renewable energies are still the main barrier to a renewable powered world, despite their many advantages (environmental effects mitigation, energy import independency, political stability (Vujic et al., 2012), among others). In addition, although some authors have agreed that renewables are theoretically and technically capable of substituting non-renewable technologies (Edenhofer et al., 2013), investors will only be attracted if renewables are also economically competitive.

Put another way, if the financial risks associated with renewables are not well understood, entrepreneurs and investors will not play a role in producing and distributing renewable energies or providing the services linked to them. Thus, it is now necessary to estimate the cost of renewables to check if they are competitive when set against non-renewables.

Concerning the second issue, the high level of unemployment is a common problem that affects a great number of countries all over the world (Markandya et al., 2016). Therefore, given the importance of the energy sector, its job creation can be of paramount importance in the present historic period of increasing challenges. Job generation is one of the benefits usually associated with renewables (Cameron and van der Zwaan, 2015), although this is still disputed (Cameron and van der Zwaan, 2015). Taking this into account, it is also necessary to analyse the employment generated by renewables to see if they are more labour intensive than their non-renewable counterparts.

Galicia is an autonomous community of Spain, located in the northwest of the Iberian Peninsula. It is divided into four provinces: A Coruña, Lugo, Ourense and Pontevedra. Galicia is bordered by the Portugal to the south, the Spanish autonomous communities of Castilla y León and Asturias to the east, the Cantabrian Sea to the north, and the Atlantic Ocean to the west. Its area is 29,575 km^2, its current population is about 2,700,000 inhabitants, and its Gross Domestic Product (GDP) is approximately 58,000 Million Euros.

Galicia has significant singularities at social and geographical levels: high level of fragmentation of the territory, a highly dispersed population and a peripheral geographical location in comparison to the rest of European regions. All these peculiarities represent a major challenge for its development. Nevertheless, Galicia is a region rich in forest and energy resources (*Xunta de Galicia*, 2014).

The energy sector plays an important role in the Galician economy. It has important energetic infrastructures such as the oil refinery located in A Coruña, the regasification plant at Mugardos, and the combined cycle power plant at As Pontes, among others (*Xunta de Galicia*, 2014). The reader can find more information about Galician power plants in *Instituto Enerxético de Galicia* (2017). On the other side of the coin, there is a huge potential for renewables in Galicia, since it is the first Spanish region in terms of forest biomass potential, without forgetting other renewables (onshore and offshore wind energies, hydroelectric power, and marine energies, among others).

Thus, assessing the costs, employment generation and, in general, the sustainability of renewable and non-renewable power plants could have a great impact on the development of Galicia.

Apart from sustainability assessment, there is a necessity of going further, looking for optimisation, in terms of maximising the contribution to sustainable development of engineering and, particularly, energy systems. It is obvious that any energy system has an impact on its surroundings, including the planet and its populations (del Caño et al., 2015). Nowadays, full-scale, strict sustainable development is not possible. However, there can be great differences in the contribution to sustainable development that alternative energy system designs bring. The final objective should be to optimise the sustainability of entire power plants or, even more, to optimise the sustainability of countries' energy grid. As a first step, the sustainability optimisation of energy subsystems should be addressed. Hence the need of finding an energy subsystem with application in a wide range of industries and sectors.

Heat exchangers are devices used in different industries including power engineering, petroleum refining, process industries, food, chemical, shipbuilding, and many others (Azad and Amidpour, 2011; Bahiraei et al., 2015; Bahiraei et al., 2017). Galicia is related to all these sectors. Shell and tube heat exchangers (STHEs) are the most frequent type of heat exchangers (Azad and Amidpour, 2011; Bahiraei et al., 2015).

In fact, STHE's adaptability to different operation conditions (Vasconcelos Segundo et al., 2017), its relatively simple manufacturing (Vasconcelos Segundo et al., 2017), robustness and reliability (Hadidi et al., 2013; Hadidi and Nazari, 2013) make this type of heat exchanger suitable for being used in several applications such as refrigeration, heating and air conditioning, power generation, chemical processes, manufacturing and medical applications (Hadidi et al., 2013; Hadidi and Nazari, 2013). Its use has also been proposed for alternative energy applications, such as marine energies (Rao and Saroj, 2017). In conclusion, STHEs play a crucial role in industries (Tharakeshwar et al., 2017), and they are expected to maintain this position in the future (Costa and Queiroz, 2008).

The sustainability optimisation of STHEs, due to their widespread use, can have not only an indirect but also a direct impact on Galicia, since many Galician industries use these devices. Moreover, it must not be forgotten that Galicia is the seat of a company specialised in the design and manufacturing of STHEs (*Industrias Técnicas de Galicia*, 2017).

2. Objectives and main gaps in the current knowledge

This PhD Thesis is a compendium of four publications addressing the sustainability assessment and optimisation of energy systems. Therefore, the present section is organised as follows: Section 2.1 focuses on the sustainability assessment of renewable and non-renewable power plants. The sustainability optimisation of a STHE is presented in Section 2.2. This section 2, and the following ones, present a brief description of the four articles. Please refer to the full publications in Appendix A for more information.

2.1. Sustainability assessment of renewable and non-renewable power plants

The first objective of this Doctoral Thesis is to compare the contribution to sustainable development of some of the most important types of renewable and non-renewable power plants throughout their life cycles.

The publications related to this research are:

- **Article No. 1**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2015. Assessing the global sustainability of different electricity generation systems. Energy 89, 473-489. doi:10.1016/j.energy.2015.05.110.
- **Article No. 2**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2016. Probabilistic life-cycle cost analysis for renewable and non-renewable power plants. Energy 112, 774–787. doi:10.1016/j.energy.2016.06.098.
- **Article No. 3**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2017. Comparative analysis of direct employment generated by renewable and non-renewable power plants. Energy 9, 147–166. doi:10.1016/j.energy.2017.08.025.

Regarding the part of this first objective addressed in **Article No. 1**, the sustainability assessment of power plants has caught the attention of a great number of authors. Some studies are focused on specific systems in a given region or country. By way of example, Kaya and Kahraman (2010) are focused on Istanbul. A similar case is Burton and Hubacek (2007), which is a study developed for Kirklees, located in the United Kingdom.

Other studies deal with systems that have very specific technologies or characteristics. For instance, Afgan and Carvalho (2002) considered specific power plants with certain characteristics, such as installed power, steam pressure, steam temperature or thermal efficiency.

As far as can be known, very few studies consider more than a specific power plant for each type of energy system. Even when they do this, they do not include conventional power plants, or fail to examine every aspect of sustainability in depth. For example, both in Varun et al. (2009) and in Dombi et al. (2014), only renewable alternatives are assessed. Moreover, the indicators employed in both studies do not cover all the sustainability pillars in depth.

It can be concluded that in the literature there is no model providing a global and general vision of the integral sustainability for all the more common power plants. Thus, the original contribution of **Article No.1** is twofold. On the one hand, its aim is to create an assessment model that makes it possible to compare the main energy systems according to integral sustainability criteria, by considering the economic, social and environmental pillars in depth. On the other hand, this is the first time that the MIVES method was applied for such a purpose in the energy sector. The reader can find in Section 3.1 more information about the MIVES method.

The model was used to assess ten alternatives throughout their life cycles, from obtaining the fuel to running the plant. Five of these were classified as non-renewable power plants: using coal, lignite, oil, natural gas and nuclear power. The other five were renewables: photovoltaic, onshore wind, mini-hydro, biomass, and high temperature solar thermal power plants.

All the alternatives were assessed against twenty seven sustainability indicators, which exceeds the number of variables included in former studies. The three classical dimensions of the integral sustainability (economic, social and environmental) were therefore assessed in depth.

As mentioned in Section 1, the current economic crisis make some sustainability aspects like costs and employment generation come to the forefront. Consequently, the economic dimension of sustainability and the employment generation of power plants were addressed in **Articles No. 2** and **3**, respectively.

Regarding the economic pillar of sustainability in the energy sector, a considerable number of authors have delved into it. Some of these studies focus on one type of energy system in a given region or country. For instance, Akdag and Güller (2010) look at wind generation in Turkey.

Other papers go further by studying the economics of different types of power plants for the same region or country. For example, De Groot et al. (2013) focus on solar and coal production facilities in South Africa.

To the best of the authors' knowledge, very few studies consider a wide range of power plant types from a general and global point of view. Furthermore, very few economic studies consider uncertainty by adopting a probabilistic approach.

Thus, the main conclusion is that there is no study providing a global, general and probabilistic vision of the economic performance for all the more common power plants. The original contribution of **Article No. 2** is twofold. On the one hand, its aim is to carry out a probabilistic assessment of the economic performance of renewable and conventional power plants all over the world. On the other, this is the first time that the MIVES-Monte Carlo method and a probabilistic levelised cost of electricity (LCOE) approach were applied for this purpose in the energy sector. The reader can find in Section 3.2 and 3.3 more information about these methodologies.

Both methods were used to assess eighteen alternatives throughout their life cycles, from the point in which the fuel is obtained to when the plant is decommissioned. Five of these were classified as non-renewable power plants: using coal, lignite, oil, natural gas and nuclear power. The remaining rely on renewable energies: onshore and offshore-wind, photovoltaic, mini-hydro, biomass, high temperature solar thermal, high temperature solar-thermal hybrid using different percentages of natural gas, tidal barrage, tidal stream and wave energy power plants.

In terms of employment generation, a large number of authors and organisations have attempted to assess how many jobs are generated through power plants. Some of these papers only focus on one type of energy system in a specific region or country (Varela-Vázquez and Sánchez-Carreira, 2015; Williams et al., 2008; among others).

Other studies go further by analysing the employment generation for different types of power plants in the same region or country (Çetin and Egrican, 2011; Llera-Sastresa et al., 2010). Still other papers deal with a specific energy system in more than one region or country. Blanco and Rodrigues (2009) is one example of this last type.

Very few studies consider employment generation for a range of power plant types in different regions or countries. Ortega et al. (2015) is one of the few that cover many different countries and several technology options. However, it is limited to renewable energies.

Rutovitz and Atherton (2009) can be considered an uncommon case in that it covers job creation from non-renewable and renewable energies across several regions and countries worldwide. Nevertheless, as it is a deterministic study, uncertainty is not considered in depth. In fact, very few manuscripts adopt a probabilistic approach. The reader can find one in Williams et al. (2008). Even in this case, it does not examine each of the most common power plants from a general and global perspective.

The main conclusion is that no study provides a global, general and probabilistic vision of direct employment generation per unit of electricity produced for all the more common power plants. Thus, the original contribution of **Article No. 3** is twofold. On one hand, its aim is to carry out a probabilistic assessment on direct employment generation from renewable and non-renewable power plants. On the other, this is the first time that an analytical model combined with a Monte Carlo simulation was applied for this purpose in the energy sector. The reader can find more information about the methodology in Section 3.4.

The model was used to assess nineteen alternatives throughout their life cycles, from the point in which the fuel is obtained to the one in which the plant is decommissioned. Five of these were non-renewable power plants, using coal, lignite, oil, natural gas and nuclear power. The rest rely on renewable energies: onshore and offshore-wind, photovoltaic, mini-hydro, biomass, high temperature solar-thermal, high temperature solar-thermal hybrid using different percentages of natural gas, tidal barrage, tidal stream, wave energy, and large-hydro power plants.

Articles No. 1, 2 and **3** has served to shed light on the sustainability assessment of renewable and non-renewable power plants, providing a deeper insight into their costs and employment generation. It can be concluded that they have successfully accomplished the first objective of this thesis.

2.2. Sustainability optimisation of shell and tube heat exchanger (STHE)

The second objective of this Doctoral Thesis is to present a new integrated methodology to optimise the sustainability of energy systems as well to test its validity and efficacy by its application to the design of a STHE.

The publication related to this research is:

- **Article No. 4**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2018. Sustainability optimisation of shell and tube heat exchanger, using a new integrated methodology. In review.

Regarding this second objective, many authors have carried out studies focused on the optimisation of STHEs, adopting different objective functions, where the economic one is probably the most common. For instance, in Balkan (2005), the author improved the classical application of the entropy minimisation principle to optimise the entropy generation caused by irreversible heat transfer in exchangers. Caputo et al. (2008) proposed a method to minimise the total discounted cost of STHEs, by using a genetic algorithm. Also looking for an economic optimisation, Hadidi and Nazari (2013) presented a new design approach for STHEs, relying on biogeography-based optimisation algorithm.

To the best of the authors' knowledge, one of the main gaps in current literature is that there are no studies addressing the sustainability optimisation of STHEs. The original contribution of **Article No. 4** is fourfold. Firstly, its aim is to propose a new integrated methodology to optimise the sustainability of engineering systems. Secondly, this is the first time that this new methodology was applied to optimise the sustainability (sustainability index (*SI*)) of STHEs. Thirdly, the *SI* can be divided into the corresponding environmental, social and economic objective functions, related to the partial sustainability indices. Therefore, a multi-objective optimisation was also addressed here. A case study previously analysed in the literature (but with other objectives) was considered (Asadi et al., 2014; Azad and Amidpour, 2011; Caputo et al., 2008; Hadidi et al., 2013; Hadidi and Nazari, 2013; Patel and Rao, 2010; Vasconcelos Segundo et al., 2017). Finally, as far as the authors are aware, this is the first time that the MIVES method was applied for optimising the sustainability of an energy system. The reader can find in Section 3.5 more information about the proposed methodology.

Article No. 4 has effectively met the second objective of this thesis.

3. Methodology

This section provides a brief description of the different methods employed in the compendium of four publications that form this Doctoral Thesis. It is divided into different subsections.

3.1. MIVES method

MIVES (*Modelo Integrado de Valor para una Evaluación Sostenible*, or Integrated Value Model for Sustainability Assessment, in translation) is a deterministic multi-criteria decision method. Due to its characteristics, MIVES presents some advantages over other multi-criteria decision making methodologies widely used in the literature. It is based on the use of requirement trees, value functions and, optionally, the Analytic Hierarchy Process (AHP). MIVES comprises seven phases (from A to G).

Phase A involves defining the problem to be solved, that is to choose or design something in line with sustainability criteria. After that, during Phase B, a basic diagram of the decision model is created: a requirement tree. This is a hierarchical scheme in which the different characteristics of the product or process to be assessed are defined in an organised way.

In Phase C, value functions come into play. They are used to transform the different magnitudes and units for the indicators into a single, dimensionless parameter called value, or satisfaction index. They also allow to consider possible nonlinearities in the assessment, by means of their shape. In fact, the different geometries make it possible to establish greater or lesser exigency when complying with the requisites for satisfying a given indicator.

The following step in MIVES entails defining the weights of each aspect taken into account in the assessment (Phase D). In some cases, this can be done directly. Nevertheless, if the requirement tree is overly complex or even if there are discrepancies among the experts, the use of AHP is recommended.

In Phase E, engineers, researchers and, in general, decision makers will define which options will be evaluated. Those alternatives will be assessed in Phase F. Finally, in Phase G, the definitive decisions are made.

The reader can find in de la Cruz et al. (2014) a complete description of the MIVES method, which was used in **Articles No. 1**, **2** and **4**.

3.2. MIVES-Monte Carlo

Uncertainty can affect specific variables for power plants and energy systems. Furthermore, there could be discrepancies among the experts caused by potential subjectivity. Nevertheless, MIVES is a deterministic method. It is therefore necessary to combine it with a technique capable of considering uncertainty, such as Monte Carlo simulation.

Monte Carlo allows one to solve a variety of problems whose analytical solution would be difficult, expensive, long, or even impossible to be obtained. The most common way of addressing an engineering problem is to transform it into a set of equations that lead to the solution. Therefore, stochastic simulation (Monte Carlo) can be performed by repeating experiments on the problem in order to find an approximate solution for those equations. Indeed, what is known as Monte Carlo simulation consists of any numerical technique based on iterative sampling with random or pseudo-random numbers to obtain an approximate solution to a problem.

The MIVES-Monte Carlo method is made up of nine phases. Phase 1 involves choosing the variables that may have a probabilistic behaviour (indicators, value function shapes and weights). The next step is to estimate the values for the deterministic (Phase 2) and probabilistic (Phase 3) variables in the model.

After that, the simulation is performed. This covers Phase 4, for generating pseudo-random values; Phase 5, for evaluating the model using the MIVES method and then Phase 6, repeating Phases 4 and 5 until convergence is achieved.

In Phase 7 a statistical analysis of the output sample is performed to obtain the distribution function for the model result, as well as its main statistical parameters (maximum, minimum, standard deviation and mean, among others).

In Phases 8 and 9, the users must interpret statistical analysis as well as collect real, final data to be used in future studies, respectively.

The foundations and detailed description of the MIVES-Monte Carlo method can be found de la Cruz et al. (2014). This method was used in **Article No. 2**.

3.3. Levelised cost of electricity (LCOE)

There are different metrics to assess the economic feasibility of a power plant. Among these are the Net Present Value (NPV), Internal Rate of Return (IRR), Pay Back Period (PBP), Benefit to Cost Ratio (BCR), and LCOE approach, among others. In the calculation process of the NPV, IRR, PBP and BCR, it is not only necessary to know the costs, but also the revenues. Thus, they are suitable indicators for assessing the economic performance of a particular investment from the point of view of the public or private investor.

Nevertheless, a study based on these metrics (NPV, IRR, PBP and BCR) can be non-representative for different countries, since the revenues are usually linked to the energy policy, which may change depending on the governing party. Due to this, it is preferable to use a technique not affected by the revenues, like the LCOE metric.

The LCOE serves to assess economic lifetime energy production and cost. It makes it possible to compare alternative technologies with differing scales of investment or operating time (Short et al., 1995).

It is important to add that the LCOE is a static measurement that looks at a snapshot of a possible price for generated energy. However, true market prices are dynamic (Yuan et al., 2014). Moreover, the uncertainty can also play a key role at the time of estimating the LCOE. In other words, it cannot be assumed that a single value used in the assessment can be associated with each input, and that this value is precise.

In order to address this problem, the LCOE calculation process can be combined with Monte Carlo simulation.

The reader can find more information about Monte Carlo simulation in de la Cruz et al. (2014). More information about the LCOE metric is provided in Short et al. (1995). The method described in this section was used in **Article No. 2**.

3.4. Analytical methods

There are two main types of procedures used to calculate employment generation in the energy sector: Input-Output (IO) and analytical methods. Both IO and analytical models have advantages and disadvantages.

In its most basic form, the IO methodology consists of a linear equation system containing productive coefficients that describe the relationship between the input used by the sector and final product (Blanco and Rodrigues, 2009; Henriques et al., 2016). Those flows are registered simultaneously by origin and destination in an IO matrix. This tool is intended to model the economy as an interaction of services and goods between industrial sectors and consumers (Wei et al., 2010). Consequently, there is a large data requirement from various scopes, which can be an intractable problem for developing countries. Actually, within the context of the present Doctoral Thesis, the IO methodology was found to be inapplicable.

Analytical models are the other option for estimating impact of employment on the energy sector. They are usually based on spreadsheet or database management systems. This methodology entails conducting extensive surveys (Lambert and Silva, 2012) as a way of collecting the data. This information can also be collected from previous studies (Wei et al., 2010). Analytical models' greater transparency, simplicity, as well as their ease and quickness at the time of introducing changes, make them a better option for this thesis.

The approach commonly used to calculate employment generation involves establishing the best estimate for each input value and using it in the assessment model. However, once again, uncertainty plays a key role in comparing and assessing the effects on employment of different power plants (Cameron and van der Zwaan, 2015).

As a way of addressing this problem the analytical model can be combined with Monte Carlo simulation.

The reader can find more information about Monte Carlo simulation in de la Cruz et al. (2014). The method here described was used in **Article No. 3**.

3.5. Integrated optimisation methodology

The methodology to optimise the sustainability of energy systems is, in part, based on the MIVES method (see Section 3.1). It comprises the creation of two models. Firstly, a mathematical model must be created for designing the energy system (design model). This model must include all the variables (continuous and discrete), equations, and constraints necessary for ensuring an adequate design of the system.

Secondly, it is necessary to define a MIVES-based model to assess the sustainability of the energy system (sustainability model). Once both models are defined, linking is possible, configuring the complete model to be optimised. That is, design variables of the engineering system (design model) can adopt different values. These values will be associated with diverse valid designs of the system. Each design will have its own characteristics (consumed resources, costs, environmental emissions, and so on). The outputs of the design model will define the inputs of the sustainability model, which will be used to estimate the sustainability index associated to each valid alternative.

The next step is to apply a conventional or metaheuristics simulation process to find the energy system with the highest contribution to integral sustainability. One of the easiest conceptual technique consists in applying the Monte Carlo simulation. With this technique a random search is carried out and, after the simulation, the design with the highest contribution to sustainable development can be identified.

Another conceptually simple alternative is to apply a brute force approach (exhaustive search). Brute force optimisation methods try to calculate all the solutions of a problem, so that the best one can be identified. If the variables are continuous, the number of possible solutions is infinite. Therefore, the solutions that will be assessed are those which are defined according to a certain precision for each continuous variable.

The problem of optimising the sustainability of an energy system can also be understood as a multi-objective optimisation problem, where each of the sustainability dimensions can be defined as an objective function. In these types of problems the solution consists in a set of optimal results (known as Pareto-optimal ones) instead of a single solution (Deb et al., 2002). Genetic algorithms are adaptive and semi-stochastic optimisation methods based on several strategies from biological evolution (Floudas and Pardalos, 2009). There are a considerable number of multi objective optimisation genetic algorithms. One of them is the non-dominated sorting genetic algorithm, called NSGA, proposed by Srinivas and Deb (1994). It was later modified and improved by Deb et al. (2002), who addressed its main criticisms (lack of elitism, computational complexity, among others). The result is NSGA-II, one of the most widely used techniques to solve optimisation problems in the energy sector.

Apart from these techniques, other search methods can be used, such as tabu search, simulated annealing, and other genetic algorithms, among other options (Floudas and Pardalos, 2009).

The methodology here described was used in **Article No. 4**. In fact, the three concisely described optimisation techniques (Monte Carlo, exhaustive search and NSGA-II) were applied to optimise the sustainability of a STHE.

4. Results and discussion

This section provides a short description of the main results presented in the compendium of four publications that forms this Doctoral Thesis. It is divided into two subsections. Section 4.1 shows the results associated with the first objective of the thesis. On the other hand, the STHE sustainability optimisation results (second objective) are included in Section 4.2. The reader can find more information in Appendix A.

4.1. Sustainability assessment of renewable and non-renewable power plants

At the time of comparing different power plants, it is necessary to consider a time period long enough to include all of the predictable circumstances that could happen and the assessable aspects that could arise.

As mentioned in Section 2.1, in **Article No. 1**, the sustainability assessment was carried out throughout each power plant's life cycle, excluding the decommissioning stage. This aspect was not included due to the absence of reliable data for some of the indicators for some power plants.

The high temperature thermal solar plant obtained the highest contribution to sustainable development due to its favourable results in the social and environmental areas. Despite this, its potential use in Galicia is not very promising. In fact, its expansion will probably take place in the regions and countries located in the so-called Sunbelt (within 35º of the Equator).

Following close behind are the onshore wind farm and photovoltaic solar plant, handicapped by a slightly lower social contribution. Once again, this last option is not likely to experience a huge expansion in Galicia for the same reason as in the case of the high temperature thermal solar plant. On the contrary, Galician weather and orographic conditions are suitable for the growth in wind power. In point of fact, in the first years of this century, the installed wind power capacity in Galicia grew enormously. Despite its recent stagnation, a new growth is expected for the next years.

The mini-hydraulic plant is the fourth option in terms of sustainability. This option can achieve good economic performances, under certain conditions (in reality, it is capable of the best and worst). It is also attractive from an environmental point of view. Nevertheless, its contribution to the social dimension is not amongst the highest ones. On the one hand, its operation produces few employment opportunities. Its employment generation during the construction stage depends on the way it is carried out. In other words, if the construction is painstakingly executed, the machinery involved is therefore reduced to avoid harming the environment. In such cases, a considerable job creation can be achieved. In the rest of cases, the opposite occurs. On the other hand, accidents may happen if dams or reservoirs flood, the retaining wall breaks or becomes unsettled, landslides occur and a considerable amount of water escapes. In this line, Galicia has a considerable hydropower potential.

Close behind, the next candidate is the first conventional alternative on the list, the natural gas-fired plant. It stands out as one of the most balanced option. Its presence in the Galician energetic mix is significant, with more than 1200 MW installed.

The nuclear energy resulted to be the most attractive option economically. On the other side of the coin, it generates radioactive waste. To this should be added that there could be catastrophic impacts from accidents. After the recent Fukushima Daiichi nuclear disaster, this type of energy is being questioned all over the world.

Biomass is the least sustainable renewable energy system. Even though it may be considered neutral in CO_2 emissions, during the transformation and combustion stages, nitrogen oxides and sulphur, as well as ash and other substances can be emitted. Nevertheless, in social terms, this is one of the options that contribute most to sustainable development. In the particular case of Galicia, biomass power plants are likely to achieve better results than the ones obtained in **Article No. 1**. There are compelling reasons for that. Exploitation of forest biomass would contribute to forest cleaning, reducing fire and pest risks. It should not be forgotten that, almost every year, a wave of fires devastates Galician forests.

Finally, systems that are fired by petroleum, coal and lignite occupy the last three positions. Among other reasons, they are by far the most contaminating ones. During their working lives, these systems contribute to global warming and acidification. Along with producing other kinds of impact, these systems pollute the air with heavy metals and carcinogenic substances.

The results obtained in **Article No. 1** were compared with the ones in the existing literature. Many studies show similar results (Dombi et al., 2014; Kahraman et al., 2009; Kaya and Kahraman, 2010). In all other cases, the differences are due to justifiable reasons, usually related to the absence of key indicators in the literature.

While the results seem to make sense, there was room for improvement, in particular with regard to the assessment of specific indicators. First, it was found that assessing the economic dimension of power plants through MIVES can lead to some inconsistencies in the results. Secondly, due to the great deal of variation in capacity factors, it was concluded that it would be preferable to express the employment generation per unit of electricity generated. To these should be added that the dismantling stage as well as the uncertainty (technology, labour costs, planning and process efficiency, capacity factor, lifetime, fuel, geopolitical situation, among others) can have an impact on both the costs and job creation. These factors may cause variations in the results presented in **Article No. 1** for specific types of power plants. Therefore, all these arguments brought with it the necessity to go in-depth in the assessment of these two indicators, giving rise to **Articles No. 2** and **3**.

As mentioned in Section 2.1, a probabilistic life-cycle cost analysis for renewable and non-renewable power plants was conducted in **Article No. 2**. The life cycle stages considered in this study were: obtaining, treating and transporting the fuel or raw materials, and building, running and decommissioning the plant.

All the non-renewable alternatives presented the same more frequent interval for the LCOE ([50, 100) €/MWh), while renewables obtained a higher modal interval (more expensive), only with one exception (onshore wind). In other words, non-renewable power plants are likely to be cheaper than their renewable counterparts. However, renewable alternatives seem to be competitive options in many cases, even achieving greater results than certain non-renewable alternatives.

Coal, lignite and nuclear power plants were the non-renewable alternatives with the best results. These three power plants were closely followed by the best-ranked renewable alternative, that is, onshore wind. It seems to be a competitive option with a LCOE that, in the majority of cases, is within the range [50, 100) €/MWh. This is in line with the results obtained by the Department of Energy and Climate Change of the UK government (2013), the International Energy Agency (2010) and the World Energy Council (2013).

The power plants fired by oil and natural gas were the following two options, with higher mean and maximum values. This is because many of these power plants (especially oil-fired ones) have low capacity factors, as a result of working in intermediate and peak load, instead of baseload, configurations.

Biomass power plants resulted to be one of the most attractive renewable options from an economic point of view, which contradicts the results obtained in **Article No. 1**. Indeed, the difference between the LCOE obtained by biomass and the one obtained by coal or lignite is due to the fact that the former is a more intensive option in terms of fuel consumption.

The mini-hydraulic plant obtained a wide range of possible values, being capable of the best and worst. This is in accordance with the World Energy Council (2013).

Photovoltaic and offshore wind options were two of the following alternatives in terms of best economic performance. Their minimum values are not excessively high. However, they can reach very high maximum values, under certain conditions.

High temperature solar-thermal plants with and without hybridisation have obtained what can be considered middling results in terms of economic performance, if one takes into account all the alternatives assessed in this article, including the non-mature ones.

Regarding marine energies, tidal power plants (also known as tidal barrage) obtained results that are competitive with those reached by other renewable power plants. In fact, if the financial and political conditions are suitable, tidal barrages can get acceptable results. Nevertheless, the environmental impact of these structures has generally hindered their wide-scale application (Esteban and Leary, 2012). Tidal stream and wave energy options got the worst results out of all the alternatives, as would be expected, given that they are in their infancy.

Article No. 2 was also useful to detect why MIVES can lead to some inconsistencies in the results of certain types of power plants. Nevertheless, this only happens exceptionally. The reader can find the main reasons in Section 5.3 of **Article No. 2**.

As indicated in Section 2.1, in **Article No. 3** a probabilistic assessment on direct employment generation from renewable and non-renewable power plants is performed. It includes the direct jobs associated with the construction and installation stages, the manufacturing of the components, the fuel procurement, the operation and maintenance phases and the final step: decommissioning of the plant at the end of its lifetime.

Coal power plants obtained middling results. That may seem rather surprising, since non-renewable power plants require a stage of fuel procurement, in which direct jobs are created. Nevertheless, extractive industries do not employ many people, since growing mechanisation and automation translates into fewer jobs. Lignite power plants presented higher results. This is due to the lower calorific power of lignite in comparison with coal.

Similarly, the results for oil-fired power plants are also far from the options with the largest direct job creation. The results for natural gas are also in the same vein. Natural gas power plants generates more jobs during the operation and maintenance stages, while the ones fired by oil generate more jobs during the fuel supply stage.

Nuclear energy is a very labour intensive option during the construction, installation and decommissioning stages. In fact, it is the alternative with the higher input values for those variables. On the other hand, nuclear power plants are the least intensive non-renewable options in terms of fuel consumption. Furthermore, for technical reasons, they only can work in baseload configurations. Therefore, this type of power plant generates fewer jobs (in the fuel chain production) than all other non-renewable alternatives.

For onshore wind farms, the job creation per output of electricity is far from the highest-performing alternatives. This may seem to be surprising; since it is a common belief that renewables generate more jobs than non-renewable plants. Nevertheless, this alternative is a sufficiently mature technology. Its efficiency in construction, installation and fabrication processes is considerably high, so that an intensive workforce is not needed.

Offshore wind farms obtained higher-performing results than the onshore technology option. Construction, installation and decommissioning activities that take place off-rather than on-shore need a higher number of employees.

Photovoltaic resulted to be the most attractive option in terms of direct employment generation, closely followed by other renewable alternatives, including biomass, mini-hydro or high temperature solar thermal plants. In the case of mini-hydro, its employment generation depends on the way in which its construction and decommissioning stages are executed.

Biomass power plants were the second option in terms of the highest mean and mode results. They usually need more workers than non-renewable options for obtaining fuel, as well as running and maintaining phases.

The results for high temperature solar thermal plants are founded on the strong need for a labour force during their construction and installation, and during their decommissioning as well. The hybridised alternatives present a certain level of fuel consumption, which is associated with direct employment generation.

Tidal barrage and large hydro options seem to be the two lowest performing options in terms of direct employment generation. Nevertheless, the reader should bear in mind that no decommissioning stage was assumed for either options. Obviously, dismantling their civil engineering works can generate a great number of job posts. Nevertheless, this can be technically challenging. This is the reason why those activities, where possible, are avoided.

Ocean energies (tidal stream and wave energies) can be considered an emerging sector. Their lack of maturity means job creation is high, since there is much room for improvement, especially concerning process efficiency. At present, both are attractive options. However, their direct employment generation is expected to diminish in coming years.

The results obtained in **Article No. 3** were compared with the ones in the existing literature. Many studies show similar results (Tourkolias and Mirasgedis, 2011; Wei et al., 2010).

It is necessary to make some clarifications about the results. As stated by Lesser (2010), the need for more workers to produce a given amount of electricity is often considered a benefit, which is not entirely true. That is, a higher employment generation per output of electricity can be seen as less efficient. This point is also related to capacity factors. A low capacity factor produces a higher number of jobs per GWh. Nevertheless, the installation is inoperative over a large part of the year; this is the case with certain renewables, dependent on phenomena such as wind or solar radiation.

It is expected that the results obtained in **Articles No. 2** and **3** could alter the ranking presented in **Article No. 1**. However, major differences are not likely to happen.

4.2. Sustainability optimisation of shell and tube heat exchanger (STHE)

As can be seen from Section 2.2, **Article No. 4** comprises the sustainability optimisation of a STHE. In particular, the design of a STHE to sub-cool condensate from a methanol condenser from 368.15 K (95 ºC) to 313.15 K (40 ºC) is addressed. Brackish water was used as coolant with a temperature increase from 298.15 K (25 ºC) to 313.15 K (40 ºC).

Three different scenarios were considered (baseline, optimistic and pessimistic) by varying the value of some of the parameters of the models (energy cost and discount rate). The three optimisation techniques described in Section 3.5 were used in order to find the most sustainable design. For the NSGA-II algorithm, it was necessary to select one of the solutions from the Pareto optimal frontier: the one with the highest sustainability index (*SI*).

For the three scenarios, the sustainability index achieved with the brute force approach was higher than the ones obtained by applying the Monte Carlo and NSGA-II algorithms. Nevertheless, the three methodologies provided very similar results.

The best design presented a sustainability index of 0.7941 for the baseline scenario. Similarly, the solutions for the optimistic and pessimistic cases took a value of 0.7986 and 0.7385, respectively. All these sustainability indices can be considered as quite good solutions, since they are close to the best possible solution (*SI* = 1) and far from the less sustainable one (*SI* = 0). On the other hand, 0.2791 and 0.5215; 0.2825 and 0.5432; 0.2709 and 0.4408 were the lowest and average sustainability indices (*SI*) obtained from the baseline, optimistic and pessimistic cases, respectively. That provides an idea about the capacity of the proposed integrated method to optimise the sustainability of an energy system.

As the *SI* can be broken down as the sum of an economic index (*EI*), a social one (*SOI*) and an environmental index (*ENI*), the optimisation of each one of these sub-indices was also carried out. The *SIs* achieved employing the *EI* or *ENI* as objective functions were similar to the ones obtained when the *SI* was the objective function. In fact, the NSGA-II technique provided exactly the same design when the *SI* or the *ENI* were established as the objective. However, the previous tendency was not true for the *SOI*.

As mentioned in Section 2.2, the optimisation of the STHE analysed in **Article No. 4** was previously addressed by other authors. Nevertheless, all of them focused only on the total costs minimisation (economic optimisation). Therefore, as a way of determining effectiveness and validity of the proposed methodology, the results were compared with the ones in literature. For that purpose, the values for the decision variables associated to the minimum cost obtained by Asadi et al. (2014), Caputo et al. (2008), Hadidi et al. (2013), Hadidi and Nazari (2013), Patel and Rao (2010) and Vasconcelos Segundo et al. (2017) were introduced in the present model, for the baseline scenario. In this way, this process verified that with the proposed methodology there is a reduction in the total costs.

5. Conclusions

This section shows the main conclusions extracted from this Doctoral Thesis. It is divided into two subsections. Section 5.1 provides the conclusions associated with the first objective of the thesis. On the other hand, the STHE sustainability optimisation conclusions (second objective) are included in Section 5.2. The reader can find more information in Appendix A.

5.1. Sustainability assessment of renewable and non-renewable power plants

In **Article No.1** the problem of assessing the sustainability of different types of power plants was successfully addressed. The paper proposed a model that treats all the classical sustainability pillars in depth.

The model was used to assess the sustainability of five non-renewable and five renewable power plants. This is the first time that all the most common types of power plants were assessed by considering intermediate input values, close to the modal ones, and not specific values from real power plants. Specific values can be non-representative of each type of power plant, since there can be atypical cases. These exceptions can provide a wrong idea of which is the modal contribution of each type of technology to sustainable development.

From the results obtained, the general conclusion is that there is a wide difference in the sustainability index, which measures the contribution to sustainable development, between the two first alternatives (high temperature solar-thermal plant and onshore wind farm) and the last three alternatives (oil fired power plant, coal-fired power plant and lignite thermal power plant).

In general, renewable power plants got the highest sustainability indices, with the exception of biomass. On the other hand, their non-renewable counterparts obtained lower values.

Major trends may alter the reality of input values in the future, making it necessary to modify the model. This could, for instance, be the case with changes in fuel prices, environmental taxes for externalities and technological maturity processes for specific technologies.

Regarding the methodology, this study showed that MIVES is not only valid but also suited to being applied in the energy sector and, specifically, in the sustainability assessment of power plants. It is a relatively simple method to apply, from which useful information can be extracted.

In **Article No. 2**, the problem of assessing the life cycle costs of renewable and conventional power plants was satisfactorily addressed. In fact, two new probabilistic models were proposed: the first one based on the MIVES-Monte Carlo method, while the second was grounded on the calculation of the LCOE combined with a Monte Carlo simulation.

The proposed models were used to assess the economic performance of five non-renewable and thirteen renewable power plants. This was the first time that all the most common types of power plants were assessed by considering distribution functions for the input values that represent the majority of the possible real cases, and not specific values from real power plants.

From the results obtained, the general conclusion is that variability and uncertainty play key roles in assessing and comparing different power plants from an economic point of view. Non-renewable power plants (coal, lignite, oil, natural gas and nuclear) are still the most competitive options. Generally, renewable power plants obtained worse results. Nevertheless, this study demonstrated that renewable alternatives can be competitive under certain conditions. In particular, some renewables such as onshore wind, mini-hydro, biomass or even solar power plants, achieved LCOEs that on some occasions are lower than those obtained by the non-renewable options. Marine energies, especially tidal stream and wave energy, got the worst results due to their low level of maturity.

Regarding the methodology, this study showed that the MIVES Monte Carlo method may be suited to being applied in the energy sector. Nevertheless, it has its drawbacks and a critical analysis of the results is always required.

In **Article No. 3**, the problem of assessing direct employment generation for power plants was adequately addressed. A new analytical model combined with Monte Carlo simulation was proposed.

It was used to assess the performance of five non-renewable and fourteen renewable power plants. This was the first time that all the most common power plants were assessed by considering distribution functions for the input values that represent the majority of possible real cases, and not specific values from real cases. It was also the first time that direct employment generation was estimated for the decommissioning stage.

From the results obtained, the general conclusion was that uncertainty plays a key role when power plants are being compared and assessed from the employment point of view. Therefore, there is no better option for all the real cases.

According to the results, some of the most mature renewables, such as photovoltaic, biomass or mini-hydro, and some of the less mature ones, like tidal stream and wave energy, resulted to be the technologies with the highest direct employment generation.

On the other hand, this study demonstrated that non-renewable alternatives can compete with renewables under certain conditions. It also showed that not all the renewables present high direct employment generation.

Regarding the methodology, this study confirmed that analytical models can be applied at national and international levels.

5.2. Sustainability optimisation of shell and tube heat exchanger (STHE)

In **Article No. 4** a new integrated methodology to optimise the sustainability of engineering systems was presented. It was satisfactorily tested by addressing the problem of maximising the integral sustainability of a STHE, previously analysed in the literature. Three optimisation techniques (brute force, Monte Carlo and NSGA-II) were applied to find the optimum solution, providing similar results.

From the results obtained, the general conclusion is that methodologies like the one presented can be very helpful in obtaining the most sustainable design from all possible alternatives for a specific application. In fact, for the case study analysed in this paper, the possible designs presented a sustainability index ranging from 0.2791 (worst design) to 0.7941 (optimal, or sub-optimal solution) for the baseline scenario. It is obvious that there is a great difference in the contribution of both extreme designs to integral sustainability.

It was also demonstrated that, even under the plausible worst conditions, it is always worth looking for the most sustainable design.

6. Future developments

This Doctoral Thesis represents progress in the fields of sustainability assessment of power plants and sustainability optimisation of energy systems. Nevertheless, the results obtained served to open the doors to potential improvements for future research. In fact, a considerable part of the here stated as future developments is already done. Nonetheless, it was not included in this document, since it is not still in the format of a research article and it was not send to be published yet. The reader can find out more information in Appendix B. This section is divided into two different subsections, each one of them associated with one of the main objectives of this thesis.

6.1. Sustainability assessment of renewable and non-renewable power plants

The model presented in **Article No. 1** could be improved in two essential ways. On the one hand, there may be uncertainty in terms of the values that some of the model's parameters may take. It is therefore necessary to incorporate an uncertainty analysis system into the model (for instance Monte Carlo simulation). In this way, the differences between the electricity generation systems could be analysed in greater detail.

In addition, the model could be gradually expanded, incorporating new indicators that make it possible, for example, to assess the impact of dismantling the power plants at the end of their service life. The possibility of including new economic, social and environmental indicators could be studied, as a way of generating a more complete model. Another improvement option would be to add a fourth pillar or category: the technical-functional one, to cover the integration into the energy network, supply reliability and safety, among other indicators.

Regarding the economic dimension, new indicators such as the costs associated with possible accidents or natural disasters, among others, should complement the economic analysis performed in **Article No. 2**.

On the other hand, **Article No. 3** is focused on job numbers. However, this is only one part of the story. The quality of the jobs is as important as the quantity. There is a wide range of issues such as working conditions, job security, worker rights, wages, career prospects, and the level of trade union participation, among others, that should be analysed. It is also necessary to study the indirect and induced employment generation.

6.2. Sustainability optimisation of shell and tube heat exchanger (STHE)

The MIVES model presented in **Article No. 4** could be gradually expanded. This is to incorporate new economic, social and environmental indicators. There is also a need to consider all the components of the STHE as well as their manufacturing processes.

Regarding the methodology, other optimisation techniques, like simulated annealing, tabu search and other genetic algorithms, could be incorporated into the proposed integrated methodology. Their results could be compared with the ones presented in this thesis to analyse the computational advantages and disadvantages.

Additionally, the present integrated methodology could be applied to optimise the sustainability of complete energy systems comprising a large amount of design variables, such as an entire power plant, among other options. Solving the same or similar case study but, this time, increasing the number of variables could be a preliminary line of action.

7. References

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Appendix A: Main publications

Article No. 1

Assessing the global sustainability of different electricity generation systems

Juan José Cartelle Barros, Manuel Lara Coira, María Pilar de la Cruz López, Alfredo del Caño Gochi

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Probabilistic life-cycle cost analysis for renewable and non-renewable power plants

Juan José Cartelle Barros, Manuel Lara Coira, María Pilar de la Cruz López, Alfredo del Caño Gochi

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Comparative analysis of direct employment generated by renewable and non-renewable power plants

Juan José Cartelle Barros, Manuel Lara Coira, María Pilar de la Cruz López, Alfredo del Caño Gochi

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Article No. 4

Sustainability optimisation of shell and tube heat exchanger, using a new integrated methodology

Juan José Cartelle Barros [a], Manuel Lara Coira [b], María Pilar de la Cruz López [a], Alfredo del Caño Gochi [a]

[a] Departamento de Ingeniería Civil, Escuela Politécnica Superior (EPS), Universidade da Coruña (UDC), Campus de Esteiro, C/Mendizábal s/n, 15403, Ferrol (A Coruña), Spain.

[b] Departamento de Ciencias de la Navegación e Ingeniería Marina, Escuela Politécnica Superior (EPS), Universidade da Coruña (UDC), Campus de Esteiro, C/Mendizábal s/n, 15403, Ferrol (A Coruña), Spain.

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Appendix B: Complete model

Complete model

As mentioned in Section 6 of the Introduction, this Doctoral Thesis has comprised more research tasks than the ones included in the four articles. Part of these tasks are finished, while the remaining are in progress. Nevertheless, the additional results were not included since they are not in the form of an article. Therefore, the aim of this appendix is to briefly describe them.

The model presented in **Article No. 1** was expanded by adding new indicators. The dismantling stage was also included. An uncertainty analysis system was also incorporated, by combining MIVES with Monte Carlo simulation.

Some of the indicators included in the complete model were previously analysed in **Articles No. 1**, **2** and **3**. Obviously, the common indicators will not be described again, since the reader can find the all the necessary information in the publications included in this thesis.

Regarding the economic dimension, the levelised cost of electricity (LCOE) indicator was considered, by using the results presented in **Article No. 1**. Additionally, new indicators were included in order to assess economic issues such as the costs associated with accidents and natural disasters, the investors' interest, among others. A Delphi analysis is being used to assess these new indicators in a qualitative way. A panel of experts with more than 10 years of experience in the energy sector in the international arena was consulted. The analysis is not finished yet, since Delphi exercises are made of several rounds.

The social dimension is also being analysed in greater detail. Apart from the indicators studied in **Article No.1** and the direct employment generation discussed in **Article No. 3**, new indicators were incorporated. For example, the probability and the impact of possible accidents, the probability and impact of possible terrorist attacks, the NIMBY (Not In My Back Yard) phenomenon, among many others. Again, the evaluation of the new indicators is being carried out through a Delphi analysis. For the indicators related to the accidents in the energy sector, the historical data is also being taken into account.

The environmental impacts are being analysed in a different way in comparison with **Article No. 1**. In this occasion, the different impact categories are being studied separately. In fact, the life cycle assessment is being done by assuming the International Reference Life Cycle Data System recommendations. Some examples of impact indicators are: acidification, climate change including biogenic carbon, ionizing radiation, ozone depletion, land use, among others. The GaBi software and its databases were used to collect the data for the different indicators, for different types of power plants, all over the world. The correlation of input distributions was based on rank order correlations (also known as Spearman correlation coefficients). Different weightages were used.

A technical or functional pillar was also added. Its aim is to assess parameters such as the energy security, disruptions in the energy supply, stability and reliability, among others. These new indicators are being assessed qualitatively by a Delphi process.

Appendix C: Resumo estendido

(Extended abstract in Galician Language)

Introdución

Motivación

A día de hoxe acéptase que existen límites para o crecemento (Meadows et al., 2004). De feito, de mantérense as tendencias actuais, chegará un momento no que os ecosistemas e a poboación mundial non serán capaces de soportar os impactos derivados da actividade humana (Bouvier e Grant, 1994). Polo tanto, estanse comezando a implantar medidas para protexer ás xeracións actuais e futuras das consecuencias de superar ditos límites.

Sustentabilidade integral (Nacións Unidas, 1992) e desenvolvemento sustentable (Nacións Unidas, 1987) son dous termos que adquiriron unha importante notoriedade en case calquera sector, incluíndo, entre outros, a economía e a industria en xeral e, en particular, os sectores da construción e a enerxía. Ambos conceptos van mais alá dos aspectos puramente medioambientais, incluíndo cuestións económicas, sociais e incluso técnicas.

Por outra banda, os gobernos dos diferentes países afrontan o reto de garantir as condicións necesarias para un axeitado desenvolvemento da nación. A enerxía xoga aquí un papel moi importante (Çetin e Egrican, 2011; Fröling, 2011; Wilson et al., 2013). Polo tanto, todo país debe basear o seu sistema enerxético na existencia de recursos abundantes e de calidade, obtidos a prezos competitivos, e facilmente transportados. So desta forma é posible asegurar un subministro enerxético continuado.

Resulta necesario clarificar que o sistema enerxético ideal (eficiente, económico, libre de riscos, respectuoso co medio) non existe. Noutras palabras, todas as clases de centrais eléctricas presentan desafíos dalgún tipo, así coma riscos que deben ser tomados en consideración (Vujic et al., 2012).

Con todo, cada vez resulta mais necesario abordar a avaliación da sustentabilidade integral de centrais eléctricas, tanto renovables coma convencionais, ao longo dos seus ciclos de vida. Ademais, na situación actual de crise económica, dous aspectos relacionados coa sustentabilidade integral acadaron unha importancia, se cabe, maior: os custos e a xeración de emprego.

Na actualidade aceptase que os custos seguen a ser a principal barreira para o crecemento das renovables, a pesares das múltiples vantaxes que presentan (Vujic et al., 2012). Por tanto, resulta indispensable estimar de forma obxectiva e precisa o custo das renovables para comprobar ata que punto, e baixo que condicións, poden competir coas alternativas non renovables.

Compre engadir que moitos países de todo o mundo presentan grandes taxas de desemprego (Markandya et al., 2016). A creación de postos de traballo é un dos beneficios habitualmente asociados ás enerxías renovables (Cameron and van der Zwaan, 2015).

Con todo, aínda segue a haber moita controversia ao respecto. Por tanto, resulta necesario arroxar luz sobre este aspecto.

Galicia é unha comunidade autónoma española, situada no noroeste da península ibérica. Está formada por catro provincias: A Coruña, Lugo, Ourense e Pontevedra. Xeograficamente limita ao sur con Portugal, ao leste coas comunidades autónomas de Castilla y León e Asturias, ao norte co mar Cantábrico e ao oeste co océano Atlántico. A súa superficie, poboación e Produto Interior Bruto (PIB) son, respectivamente, de 29,575 km^2, 2,700,000 habitantes (aprox.), 58,000 Millóns de Euros (aprox.).

Galicia conta cun abano de singularidades espaciais e sociais, no contexto internacional, que implican desafíos diferenciais para o mercado: unha elevada fragmentación do territorio, que leva asociada unha elevada dispersión poboacional: e unha situación xeográfica periférica respecto ás rexións europeas. Con todo, trátase dunha rexión rica en recursos forestais e enerxéticos asociados a sectores económicos cun forte enraizamento no territorio (*Xunta de Galicia*, 2014).

O sector enerxético en Galicia conta cun peso específico relevante dentro da economía da rexión, existindo importantes infraestruturas enerxéticas como a refinería de petróleos da Coruña, a planta regasificadora de Mugardos, ou a central de ciclo combinado de As Pontes (*Xunta de Galicia*, 2014). Por outra banda, Galicia tamén presenta un gran potencial para o desenvolvemento das enerxías renovables, sendo a primeira rexión española en potencial de biomasa forestal, sen esquecer outras renovables, como a eólica, a hidráulica ou as enerxías mariñas.

Así pois, a avaliación dos custos e da xeración de emprego, así coma en xeral, da sustentabilidade integral de centrais eléctricas, pode derivar nun impacto positivo sobre o desenvolvemento de Galicia.

Ate o momento, o enfoque fundamental respecto á sustentabilidade foi de mera avaliación. É preciso ir mais alá, buscando a optimización, no sentido de maximizar a contribución ao desenvolvemento sustentable do sistema enerxético que se proxecta. Actualmente non é posible alcanzar un desenvolvemento sustentable absoluto (del Caño et al., 2015). Aínda así, os diferentes deseños dun sistema enerxético para unha certa aplicación, poden presentar diferenzas notables na súa contribución ao desenvolvemento sustentable. Por tanto, resulta necesario abordar a optimización no deseño de sistemas enerxéticos non moi complexos, coma primeiro paso cara a optimización da sustentabilidade de centrais eléctricas e outros sistemas complexos. Obviamente, a maior uso do sistema enerxético a optimizar, maior será o impacto dos resultados obtidos.

Neste sentido, os intercambiadores de calor son dispositivos de transferencia de calor entre fluídos empregados en múltiples industrias (Azad e Amidpour, 2011; Bahiraei et al., 2015; Bahiraei et al., 2017). En particular, os intercambiadores de carcasa e tubos son o tipo mais empregado, debido a súa adaptabilidade a diferentes condicións de operación (Vasconcelos Segundo et al., 2017), a súa robustez e fiabilidade (Hadidi et al., 2013; Hadidi and Nazari, 2013), así como ao seu relativamente simple proceso de manufactura (Vasconcelos Segundo et al., 2017).

A optimización da sustentabilidade de intercambiadores de calor de carcasa e tubos pode xerar un impacto positivo sobre Galicia, non so debido ao seu uso en múltiples industrias, tamén debido á existencia dunha empresa galega especializada no seu deseño e manufactura (Industrias Técnicas de Galicia, 2017).

Obxectivos

Esta tese está formada por catro publicacións nas que se aborda a avaliación e optimización da sustentabilidade de sistemas enerxéticos.

Avaliación da sustentabilidade de centrais eléctricas renovables e non renovables

O primeiro obxectivo desta tese consiste en comparar a contribución ao desenvolvemento sustentable dos tipos mais importantes de centrais eléctricas, tanto renovables coma non renovables, ao longo dos seus ciclos de vida.

As publicacións relacionadas con este obxectivo son:

- **Artigo No. 1**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2015. Assessing the global sustainability of different electricity generation systems. Energy 89, 473-489. doi:10.1016/j.energy.2015.05.110.
- **Artigo No. 2**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2016. Probabilistic life-cycle cost analysis for renewable and non-renewable power plants. Energy 112, 774–787. doi:10.1016/j.energy.2016.06.098.
- **Artigo No. 3**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2017. Comparative analysis of direct employment generated by renewable and non-renewable power plants. Energy 9, 147–166. doi:10.1016/j.energy.2017.08.025.

A avaliación da sustentabilidade de centrais eléctricas chamou a atención dun gran número de autores. Moitos estudos céntranse en sistemas enerxéticos específicos dun determinado país ou rexión. Outros traballos abordan unicamente tecnoloxías moi concretas (potencia instalada, factor de capacidade, eficiencia, presión e temperatura de vapor, etc.) sendo minoritario o público ao que van dirixidos.

Ata onde puido saberse, son poucos os estudos que consideran mais dun caso concreto para cada tipo de central. Incluso nestes traballos, pódense apreciar certas deficiencias, normalmente asociadas á ausencia de indicadores relevantes.

Por tanto, non existe na literatura un modelo que proporcione unha visión global da sustentabilidade integral dos diferentes tipos de centrais eléctricas. O **Artigo No. 1** aporta varias contribucións orixinais. Por un lado, presenta un modelo de avaliación que permite comparar os principais tipos de centrais respecto a súa contribución ao desenvolvemento sustentable, mediante unha análise detallada dos piares económico, social e ambiental. Por outro lado, dito modelo está baseado no método MIVES, que nunca antes foi empregado no sector enerxético con tal propósito.

O modelo empregouse para avaliar dez tipos de centrais (cinco renovables e cinco non renovables). Foron utilizados vinte e sete indicadores, o que supera con creces á media de indicadores empregados na literatura existente.

Por outro lado, unha análise mais detallada dos custos e da xeración de emprego foi abordada nos **Artigos No. 2** e **3**, respectivamente.

Con respecto aos custos, tamén foron moitos os autores que abordaron o seu estudo no sector enerxético. Con todo, as conclusións son de novo semellantes. Unha cantidade considerable dos estudos céntranse na análise de centrais concretas nun determinado país ou rexión. Algúns autores foron mais alá, analizando distintos tipos de centrais dentro dun mesmo país. Con todo, son poucos os estudos que consideran un conxunto amplo de centrais a escala global. Incluso nestes casos, o enfoque da avaliación é maioritariamente determinista.

Non existe ningún estudo que proporcione unha visión probabilista e global dos custos das centrais renovables e non renovables mais comúns. Neste sentido, pódese dicir que o **Artigo No. 2** realiza unha contribución orixinal dobre. Por un lado, leva a cabo unha análise probabilista dos custos dos diferentes tipos de centrais eléctricas todo ao longo do mundo. Por outro, dito estudo foi posible gracias ao uso de dous modelos probabilistas, un baseado no método MIVES-Monte Carlo e, o outro, nun enfoque de custo normalizado de electricidade combinado con simulación estocástica tipo Monte Carlo.

Ambos modelos foron empregados para avaliar un total de dezaoito alternativas (cinco non renovables e o resto renovables), dende a etapa de extracción de combustible ata o desmantelamento das instalacións ao fin da vida útil.

En termos de xeración de emprego, moitos autores e moitas organizacións de todo tipo intentaron profundar na análise do sector enerxético. Con todo, os traballos existentes teñen alcances similares aos xa comentados para a avaliación da sustentabilidade e os custos. É dicir, non existe ningún traballo que proporcione unha visión global e probabilista da xeración de emprego directo por unidade de electricidade producida para os tipos de centrais mais habituais. Por tanto, son varias as contribucións orixinais aportadas polo **Artigo No. 3**. Por vez primeira, neste Artigo lévase a cabo unha análise probabilista da creación de postos de traballo directos, tanto para centrais renovables coma convencionais. Ademais, é a primeira vez que se emprega un modelo analítico combinado con simulación Monte Carlo para tal propósito.

Co devandito modelo avaliáronse un total de dezanove alternativas (cinco convencionais y catorce renovables), dende a etapa de extracción de combustible ata o desmantelamento das mesmas.

Os **Artigos No. 1**, **2** e **3** serviron para profundar no coñecemento e comprensión da avaliación da sustentabilidade de centrais eléctricas, proporcionando unha análise detallada tanto da dimensión económica como da xeración de emprego. Polo tanto, é posible afirmar que o primeiro obxectivo desta tese acadouse satisfactoriamente.

Optimización da sustentabilidade dun intercambiador de calor de carcasa e tubos

O segundo obxectivo desta tese consiste no desenvolvemento dunha nova metodoloxía integrada que permita optimizar a sustentabilidade de sistemas enerxéticos de todo tipo, así como a súa aplicación a un caso concreto, que neste caso foi o deseño dun intercambiador de carcasa e tubos.

A publicación asociada a este obxectivo da tese é:

- **Artigo No. 4**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2018. Sustainability optimisation of shell and tube heat exchanger, using a new integrated methodology. En proceso de revisión.

Moitos autores levaron a cabo estudos para optimizar o deseño de intercambiadores de calor de carcasa e tubos, adoptando diferentes funcións obxectivo. A minimización dos custos é a mais habitual.

Con todo, nunca ningúen realizou un estudo no que se optimice a sustentabilidade dun intercambiador de este tipo (nin de ningún outro). Son catro as aportacións orixinais do **Artigo No. 4**. En primeiro lugar, proponse unha metodoloxía integral para a optimización da sustentabilidade de sistemas enerxéticos. A segunda aportación consiste na aplicación de dita metodoloxía ao deseño dun intercambiador de carcasa e tubos. En terceiro lugar, dado que o índice de sustentabilidade pódese dividir en varios subíndices (cada un asociado a un piar da sustentabilidade integral), é posible resolver este problema dende unha óptica de optimización multiobxectivo. Por último, o método MIVES nunca antes fora aplicado coa finalidade de optimizar o deseño dun sistema enerxético.

O **Artigo No. 4** serviu para cumprir de forma satisfactoria o segundo obxectivo proposto.

Metodoloxía

Nesta sección resúmense os aspectos mais relevantes das diferentes metodoloxías empregadas neste traballo doutoral.

Método MIVES

MIVES (Modelo Integrado de Valor para unha Avaliación Sustentable) é un método multicriterio de toma de decisións determinista. Polas súas características, presenta certas vantaxes sobre outros métodos multicriterio habitualmente empregados na literatura. MIVES baséase no uso de árbores de requirimentos, funcións de valor e, opcionalmente, o proceso analítico xerárquico. Consta de sete fases (de la Cruz et al. 2014).

Na Fase A defínese o problema a resolver. Tras isto, na Fase B, crease a árbore de requirimentos, é dicir, un diagrama básico do modelo na forma de esquema xerárquico. A árbore contén, de forma ordenada os aspectos concretos a avaliar (indicadores).

No seguinte paso (Fase C), entran en xogo as funcións de valor. Unha función de valor non é mais ca unha ferramenta matemática que permite, entre outras cousas, transformar as diferentes unidades e magnitudes dos indicadores nun único parámetro adimensional, chamado valor, ou índice de satisfacción; permiten tamén considerar non liñalidades na avaliación.

Os pesos ou importancias relativas dos diferentes aspectos incluídos na árbore de requirimentos son definidos na Fase D. Isto pódese facer de forma directa. Con todo, en casos de certa complexidade resulta recomendable usar o proceso analítico xerárquico (*Analytic Hierarchy Process*: AHP).

Na Fase E defínense as alternativas a avaliar. Ditas alternativas son avaliadas na seguinte fase (Fase F). Por último, na Fase G, ten lugar a correspondente toma de decisións.

MIVES Monte Carlo

A incerteza pode afectar a certas variables das centrais eléctricas e dos sistemas enerxéticos. Con todo, MIVES é un modelo determinista. Por tanto, necesita ser combinado cunha técnica que permita ter en conta a incerteza, coma por exemplo a simulación de tipo Monte Carlo (de la Cruz et al. 2014).

Por simulación de tipo Monte Carlo enténdese calquera técnica numérica baseada na mostraxe iterativa con números aleatorios ou pseudo-aleatorios, que permite obter unha solución aproximada a un problema.

O método MIVES-Monte Carlo consta de nove fases. Na Fase 1 defínense as variables a tratar de forma probabilista (indicadores, pesos e funcións de valor poden verse afectadas pola incerteza). O seguinte paso consiste en estimar os valores de entrada ao modelo, tanto para as variables deterministas (Fase 2) como para as probabilistas (Fase 3).

A continuación, procédese coa simulación. É dicir, na Fase 4, xéranse os números pseudo-aleatorios. Na Fase 5 realizase a avaliación mediante a aplicación do método MIVES. A Fase 6 consiste en repetir as dúas fases anteriores ata alcanzar a converxencia nos resultados.

Posteriormente á simulación (Fase 7), é preciso realizar unha análise estatística dos resultados, co obxectivo de obter a función de distribución resultante, así coma os valores dos principais parámetros estatísticos (máximo, mínimo, media, entre outros).

Nas Fases 8 e 9, respectivamente, o usuario debe interpretar os resultados e tomar decisións; e recompilar os datos reais para aprender dos mesmos e mellorar en futuras avaliacións.

Custo normalizado de electricidade

Existen múltiples métricas que permiten avaliar a factibilidade económica dunha central eléctrica (valor actual neto, taxa interna de retorno, cociente custo-beneficio, entre outras). Con todo, a maioría destas técnicas necesitan calcular os custos, e os beneficios. Ditos beneficios soen estar ligados á política enerxética de cada país. Por tanto, se o que se pretende é obter unha visión realista e obxectiva do desempeño económico dos distintos tipos de centrais eléctricas, é preciso usar un método independente dos beneficios, coma o custo normalizado de electricidade (CNE).

O CNE serve para avaliar o custo asociado á produción de electricidade, en unidades monetarias, todo ao longo do ciclo de vida dunha central. Desta forma é posible realizar comparacións entre alternativas con diferentes escalas de inversión e vida útil (Short et al., 1995).

Pese as súas vantaxes, o CNE é unha medida estática que aporta información sobre unha das múltiples situacións que poden ocorrer na realidade. É dicir, os prezos dos mercados son dinámicos (Yuan et al., 2014) e ademais, a incerteza xoga un papel importante nos mesmos. Por tanto, é necesario combinar esta métrica cunha técnica, coma a simulación e Monte Carlo, capaz de ter en conta a incerteza (de la Cruz et al. 2014).

Modelos analíticos

Existen dous tipos de técnicas para o cálculo da xeración de emprego no sector enerxético: métodos de entradas e saídas, en inglés *input-output* (Blanco e Rodrigues, 2009; Henriques et al., 2016); e métodos analíticos (Lambert e Silva, 2012; Wei et al., 2010). Ambos presentan vantaxes e desvantaxes.

Os métodos *input-output* modelan a economía como unha interacción de bens e servizos entre sectores industriais e consumidores. Por tanto, permiten calcular os postos de traballo directos, indirectos e inducidos, de forma neta. Agora ben, é preciso dispor dunha gran cantidade de datos, bastante pouco habituais no caso de países en vías de desenvolvemento, e incluso de economías emerxentes. Logo, no contexto desta tese, a técnica *input-output* resultou ser inaplicable.

Os modelos analíticos son a outra opción. Soen estar baseados no uso de bases de datos e follas de cálculo. Son mais sinxelos e transparentes. Ademais, este tipo de modelos permiten introducir cambios e modificacións de forma rápida e sinxela. A isto hai que engadir unha menor necesidade de datos económicos. Agora ben, pese a súas vantaxes, o cálculo desta técnica soe limitarse aos postos de traballo directos.

De novo resulta necesario combinar os modelos analíticos cunha técnica, coma Monte Carlo, capaz de considerar a incerteza (de la Cruz et al. 2014).

Metodoloxía integrada de optimización

Baséase na creación de dous modelos. Un primeiro modelo, de deseño, que inclúe todas as variables, ecuacións e restricións necesarias para unha correcta definición do sistema que se pretende optimizar. Un segundo modelo, de avaliación, baseado no método MIVES. Unha vez definidos ambos modelos é posible conectalos, xerando o modelo completo a optimizar. Noutras palabras, as variables do primeiro modelo poden adoptar diferentes valores. Cada conxunto de posibles valores está asociado a un deseño válido. Cada deseño terá a súas características (custos, consumo de materiais, impactos sobre o medio, etc.). Por tanto, as saídas do primeiro modelo poden empregarse para calcular as entradas ao modelo MIVES. Así mesmo, este último modelo emprégase para estimar o índice de sustentabilidade asociado a cada deseño.

O seguinte paso consiste en levar a cabo un proceso de simulación convencional o metaheurístico, para atopar o deseño con maior índice de sustentabilidade. Unha primeira posibilidade é aplicar Monte Carlo. Outra técnica sinxela é a busca exhaustiva combinatoria, tamén chamada de forza bruta (Floudas e Pardalos, 2009).

Dado que é posible optimizar por separado cada un dos piares da sustentabilidade integral, os algoritmos de optimización multiobxectivo tamén resultan ser apropiados. Este é o caso, por exemplo, do Algoritmo Xenético de Clasificación Non Dominada II (Deb et al., 2002), que foi empregado neste Tese.

Resultados e discusión

Neste apartado resúmense os resultados mais relevantes de cada un dos catro artigos que forman esta tese.

Avaliación da sustentabilidade de centrais eléctricas renovables e non renovables

A enerxía termosolar de alta temperatura obtivo a maior contribución ao desenvolvemento sustentable, con resultados moi favorables nos piares social e medioambiental. Con todo, o seu potencial é reducido no caso particular de Galicia. De feito, agárdase que a expansión deste tipo de enerxía renovable teña lugar maioritariamente nas rexións situadas no chamado cinto solar.

A continuación, atópanse a eólica terrestre e a solar fotovoltaica. Esta última tamén presenta un potencial reducido para Galicia, polas mesmas razóns que a termosolar. Con todo, as condicións climatolóxicas e orográficas de Galicia si son axeitadas para o desenvolvemento da eólica. Tanto é así, que a potencia eólica instalada medrou enormemente nos primeiros anos deste século, e prevese un novo crecemento para os vindeiros anos.

A mini-hidráulica ocupa o cuarto lugar en termos de sustentabilidade integral. Por un lado, durante a súa operación apenas precisa man de obra. Por outro, a xeración de emprego asociada a súa construción depende da forma na que esta se leve a cabo, podendo ser reducida. A isto hai que engadir a posibilidade de que sucedan accidentes con impactos considerables.

O quinto lugar o ocupa a primeira alternativa non renovable: a central térmica de gas natural, cunha presenza considerable no mix enerxético galego. A certa distancia séguelle a nuclear, que aparece coma unha opción moi atractiva, economicamente. Con todo, a produción de residuos radioactivos, así como as consecuencias catastróficas derivadas de posibles accidentes prexudican a súa puntuación global.

A biomasa resultou ser a alternativa renovable menos sustentable. Pese a que se pode considerar neutra en emisións de CO_2, a súa contribución a outras categorías de impacto ambiental pode ser notable. A pesar diso, é bastante probable que a biomasa presente en Galicia unha maior contribución ao desenvolvemento sustentable ca que tería noutras rexións do mundo. O uso deste recurso serviría, entre outras cousas, para limpar os montes, e isto reduciría o risco de pragas e, sobre todo, de incendio.

Por último, as centrais térmicas que empregan fuel óleo, carbón e lignito coma combustible ocupan as tres últimas posicións. Son, con diferenza, as centrais mais contaminantes.

Pese a que os resultados obtidos no **Artigo No. 1** foron analizados de forma crítica e validados mediante a súa comparación cos da literatura existente, certos aspectos debían ser analizados en maior detalle. Isto deu lugar aos **Artigos Nos. 2** e **3**.

O **Artigo No. 2** afonda na análise da dimensión económica das centrais eléctricas. Todas as centrais non renovables obtiveron un custo normalizado de electricidade modal comprendido no intervalo [50, 100) €/MWh. As enerxías renovables obtiveron valores maiores, coa excepción da eólica terrestre, que se situou á mesma altura cas mellores centrais convencionais.

De feito, as centrais térmicas de carbón e lignito, así como as nucleares, obtiveron os mellores resultados, seguidas da eólica terrestre. As centrais térmicas de gas natural e fuel óleo situáronse a continuación, penalizadas por non funcionares sempre en réxime de carga base.

A biomasa resultou ser unha das opcións renovables mais atractivas no ámbito económico, o que contradí lixeiramente os resultados obtidos no primeiro dos artigos. Isto débese a algunhas desvantaxes metodolóxicas que presenta MIVES, baixo certas condicións. O lector pode atopar máis información ao respecto no **Artigo No. 2**. A mini-hidráulica obtivo un intervalo amplo de posibles resultados, sendo capaz do mellor e do peor.

A fotovoltaica e a eólica mariña foron as seguintes alternativas na clasificación. Baixo certas condicións, os seus custos normalizados de electricidade (CNE) poden alcanzar valores moi altos. A enerxía termosolar de alta temperatura, con e sen hibridación, obtivo resultados intermedios.

As centrais mareomotrices de barreira obtiveron resultados competitivos respecto a outras opcións renovables. Agora ben, os seus impactos ambientais frean a súa expansión. Por outra banda, tanto a enerxía mareomotriz de corrente, como a undimotriz, presentaron os peores resultados, debido a que aínda están nunha fase temperá de desenvolvemento.

Noutra orde de cousas, no **Artigo No. 3** profúndase na análise da xeración de emprego directo por unidade de electricidade producida. As centrais térmicas de carbón obtiveron resultados intermedios; isto pode parecer sorprendente, dada a existencia dunha etapa de extracción e minería. Con todo, o elevado grado de automatización reduce considerablemente a necesidade de man de obra. As centrais que empregan lignito obtiveron resultados lixeiramente superiores, derivados do menor poder calorífico deste combustible.

Na mesma liña, a creación de postos de traballo directos das centrais de gas natural e fuel óleo tamén resultaron estar lonxe das alternativas mais atractivas.

A enerxía nuclear require moita man de obra durante as etapas de construción, instalación e desmantelamento. Con todo, son as centrais non renovables menos intensivas en consumo de combustible. A isto hai que engadir que, por razóns técnicas, so traballan en carga base. Polo tanto, a súa xeración de emprego por unidade de electricidade resulta ser baixa.

A eólica terrestre presentou resultados afastados das mellores opcións, consecuencia directa da súa elevada madurez tecnolóxica. Loxicamente, a eólica mariña precisa unha maior cantidade de man de obra, aínda que so sexa como consecuencia da necesidade de persoal asociada ás actividades que non teñen lugar en terra.

A solar fotovoltaica obtivo os mellores resultados, seguida de preto pola biomasa, a mini-hidráulica e a termosolar de alta temperatura.

A mareomotriz de barreira e a gran-hidráulica presentaron a menor xeración de emprego directo. Isto débese a que non se considerou a etapa de desmantelamento xa que, debido a súa complexidade técnica, evítase sempre que é posible.

A mareomotriz de corrente e a undimotriz obtiveron taxas de creación de emprego elevadas. Resultado lóxico, xa que se trata dun sector aínda emerxente.

Optimización da sustentabilidade dun intercambiador de calor de carcasa e tubos

No **Artigo No. 4** levouse a cabo a optimización da sustentabilidade dun intercambiador de carcasa e tubos para sub-enfriar metanol condensado, dende 368.15 K

(95 ºC) ata 313.15 K (40 ºC), utilizando auga salobre coma refrixerante, cun incremento de temperatura de 298.15 K (25 ºC) a 313.15 K (40 ºC).

Empregáronse as tres técnicas de optimización descritas no apartado de metodoloxía. O índice de sustentabilidade obtido mediante a busca por forza bruta resultou ser o mais elevado. Con todo, as tres técnicas proporcionan resultados moi semellantes.

O mellor deseño presentou un índice de sustentabilidade de 0.7941, sendo 0 e 1 os límites pésimo e óptimo, respectivamente (o que non quere dicir que sexa posible chegar a 1). De feito, o peor deseño válido resultou ter un índice de sustentabilidade de 0.2791, sendo a media de todos os deseños factibles de 0.5215. Isto proporciona unha idea do potencial que presenta a metodoloxía integrada para optimizar o deseño dun sistema enerxético proposto e empregado nesta Tese.

Conclusións

Neste apartado resúmense as principais conclusións deste traballo doutoral.

Avaliación da sustentabilidade de centrais eléctricas renovables e non renovables

O **Artigo No. 1** aborda satisfactoriamente a avaliación da sustentabilidade de centrais eléctricas, tanto renovables coma non renovables, mediante a consideración dos piares clásicos da sustentabilidade, en profundidade.

A conclusión principal é que existe unha gran diferenza na contribución ao desenvolvemento sustentable entre as dúas primeiras opcións (termosolar de alta temperatura e eólica terrestre) e as tres últimas alternativas (térmicas de fuel óleo, carbón e lignito).

En xeral, as enerxías renovables presentaron maiores índices de sustentabilidade, coa excepción da biomasa.

A nivel metodolóxico demostrouse que MIVES é unha técnica válida para a súa aplicación na avaliación da sustentabilidade de centrais eléctricas.

No **Artigo No. 2** analizáronse de forma conveniente os custos de ciclo de vida de centrais eléctricas tanto renovables coma convencionais.

Dos resultados obtidos pódese concluír que a incerteza xoga un papel moi importante á hora de avaliar e comparar distintos tipos de centrais dende a óptica económica. As centrais convencionais apareceron como as opcións mais competitivas. Con todo, algunhas renovables (eólica terrestre, biomasa, mini-hidráulica e incluso as alternativas solares) tamén poden ser competitivas baixo certas condicións, incluso chegando a superar a algunhas centrais non renovables.

No metodolóxico, demostrouse que MIVES pode presentar certas desvantaxes que precisan dunha análise crítica dos resultados. O lector pode atopar máis información ao respecto no **Artigo No. 2**.

O **Artigo No. 3** contribúe de forma satisfactoria ao cumprimento do primeiro obxectivo desta tese, mediante unha análise probabilista detallada da xeración de emprego directo no sector enerxético.

A conclusión xeral é que, de novo, a incerteza xoga aquí un papel importante. Os resultados amosan que algunhas renovables (fotovoltaica, biomasa, mini-hidráulica, mareomotriz de corriente, undimotriz) seguen a ser as opcións mais atractivas a nivel de creación de postos de traballo directos. Pese a isto, as centrais convencionais poden competir coas súas homólogas renovables, baixo certas condicións.

No metodolóxico, este estudo confirmou que é posible aplicar con éxito modelos analíticos a nivel nacional e internacional.

Optimización da sustentabilidade dun intercambiador de calor de carcasa e tubos

No **Artigo No. 4** abórdase a optimización da sustentabilidade dun intercambiar de calor de carcasa e tubos mediante a aplicación dunha nova metodoloxía integrada.

A conclusión principal é que a metodoloxía empregada resulta de gran axuda á hora de seleccionar o deseño mais sustentable de entre todos os posibles para unha determinada aplicación. De feito, para o caso de estudo analizado, os deseños presentaron un índice de sustentabilidade que variou entre 0.2791 (pésimo) e 0.7941 (óptimo, ou subo-óptimo).

Por tanto, amosouse que, incluso baixo as peores condicións posibles, vale a pena buscar o deseño mais sustentable, xa que a contribución ao mesmo pode variar significativamente.

Futuros desenvolvementos

Parte do aquí incluído neste epígrafe xa está feito. Con todo, non foi incorporado á presente tese por no encontrarse en forma de artigo de investigación, publicado ou enviado para ser publicado. Para mais información, o lector pode consultar o Apéndice B.

Avaliación da sustentabilidade de centrais eléctricas renovables e non renovables

O modelo presentado no **Artigo No. 1** pode ser mellorado de dúas formas diferentes. Por un lado, debe considerarse a incerteza mediante, por exemplo, a aplicación de simulación tipo Monte Carlo. Por outro, debe estudiarse a posibilidade de incorporar novos indicadores, así coma un cuarto piar da sustentabilidade: técnico ou funcional.

Respecto á dimensión económica, débese contemplar a posibilidade de incluír novos indicadores coma, por exemplo, os que permitan medir os custos asociados a accidentes ou desastres naturais.

No tocante á xeración de emprego, é necesario ir mais alá dunha análise meramente numérica, considerando aspectos tales coma as condicións laborais, os dereitos dos traballadores, salarios, etc.

Optimización da sustentabilidade dun intercambiador de calor de carcasa e tubos

O modelo MIVES incluído no **Artigo No. 4** pode ser aumentado, mediante a incorporación de novos indicadores que, entre outras cousas, fagan posible a avaliación de todos os compoñentes do intercambiador (incluíndo a manufactura).

Metodoloxicamente, outras técnicas de optimización, tales coma o recocido simulado, a busca tabú, ou outros algoritmos xenéticos, poden ser incorporadas á metodoloxía proposta.

Adicionalmente podería empregarse a devandita metodoloxía para a optimización da sustentabilidade de sistemas enerxéticos de maior envergadura, como unha central eléctrica na súa totalidade. Como punto de partida, pódese resolver o mesmo caso de estudo pero, esta vez, aumentando o número de variables.

Appendix D: Resumen extendido

(Extended abstract in Spanish Language)

Introducción

Motivación

A día de hoy se acepta que existen límites para el crecimiento (Meadows et al., 2004). De hecho, si se mantienen las tendencias actuales, llegará un momento en el que los ecosistemas y la población mundial no serán capaces de soportar los impactos derivados de la actividad humana (Bouvier y Grant, 1994). Por tanto, se están comenzando a implantar medidas para proteger a las generaciones actuales y futuras de las consecuencias de sobrepasar dichos límites.

Sostenibilidad integral (Naciones Unidas, 1992) y desarrollo sostenible (Naciones Unidas, 1987) son dos términos que han adquirido una importante notoriedad en casi cualquier sector, incluyendo, entre otros, la economía y la industria en general y, en particular, los sectores de la construcción y la energía. Ambos conceptos van más allá de los aspectos puramente medioambientales, incluyendo cuestiones económicas, sociales e incluso técnicas.

Por otro lado, los gobiernos de los diferentes países se enfrentan al reto de garantizar las condiciones necesarias para un correcto desarrollo de la nación. La energía juega aquí un papel muy importante (Çetin y Egrican, 2011; Fröling, 2011; Wilson et al., 2013). Por tanto, todo país debe basar su sistema energético en la existencia de recursos abundantes y de calidad, obtenidos a precios competitivos, y fácilmente transportados. Sólo de esta forma es posible asegurar un suministro energético continuo.

Resulta necesario aclarar que el sistema energético ideal (eficiente, económico, libre de riesgos, respetuoso con el medioambiente) no existe. En otras palabras, todas las clases de centrales eléctricas presentan desafíos de algún tipo, así como riesgos que deben ser tomados en consideración (Vujic et al., 2012).

No obstante, cada vez resulta más necesario abordar la evaluación de la sostenibilidad integral de centrales eléctricas, tanto renovables como convencionales, a lo largo de sus ciclos de vida. Además, en la situación actual de crisis económica, dos aspectos relacionados con la sostenibilidad integral han alcanzado una importancia, si cabe, mayor: los costes y la generación de empleo.

Actualmente se acepta que los costes siguen siendo la principal barrera para el crecimiento de las renovables, a pesar de las múltiples ventajas que presentan (Vujic et al., 2012). Por tanto, resulta indispensable estimar de forma objetiva y precisa el coste de las renovables para comprobar hasta qué punto, y bajo qué condiciones, pueden competir con las alternativas no renovables.

A esto hay que añadir que muchos países de todo el mundo presentan grandes tasas de desempleo (Markandya et al., 2016). La creación de puestos de trabajo es uno de los beneficios habitualmente asociados a las energías renovables (Cameron and van der

Zwaan, 2015). Sin embargo, aún hay mucha controversia al respecto. Por tanto, resulta necesario arrojar luz sobre este aspecto.

Galicia es una comunidad autónoma española, situada en el noroeste de la península ibérica. Está formada por cuatro provincias: A Coruña, Lugo, Ourense y Pontevedra. Geográficamente limita al sur con Portugal, al este con las comunidades autónomas de Castilla y León y Asturias, al norte con el mar Cantábrico y al oeste con el océano Atlántico. Su superficie, población y Producto Interior Bruto (PIB) son, respectivamente, de 29,575 km^2, 2,700,000 habitantes (aprox.), 58,000 Millones de Euros (aprox.).

Galicia cuenta con un abanico de singularidades espaciales y sociales, en el contexto internacional, que implican desafíos diferenciales para el mercado: una elevada fragmentación del territorio, que lleva asociada una elevada dispersión poblacional; y una situación geográfica periférica respecto a las regiones europeas. Pese a ello, se trata de una región rica en recursos forestales y energéticos asociados a sectores económicos con un fuerte enraizamiento en el territorio (*Xunta de Galicia*, 2014).

El sector energético en Galicia cuenta con un peso específico relevante dentro de la economía de la región, existiendo importantes infraestructuras energéticas como la refinería de petróleos de A Coruña, la planta regasificadora de Mugardos, o la central de ciclo combinado de As Pontes (*Xunta de Galicia*, 2014). Por otro lado, Galicia también presenta un gran potencial para el desarrollo de las energías renovables, siendo la primera región española en potencial de biomasa forestal, sin olvidar otras renovables, como la eólica, la hidráulica o las energías marinas.

Así pues, la evaluación de los costes y de la generación de empleo, así como en general, de la sostenibilidad integral de centrales eléctricas, puede derivar en un impacto positivo sobre el desarrollo de Galicia.

Hasta el momento, el enfoque fundamental respecto a la sostenibilidad ha sido de mera evaluación. Sin embargo, es necesario ir más allá, buscando la optimización, en el sentido de maximizar la contribución al desarrollo sostenible del sistema energético que se proyecta. A día de hoy no es posible alcanzar un desarrollo sostenible absoluto (del Caño et al., 2015). Sin embargo, los diferentes diseños de un sistema energético para una cierta aplicación, pueden presentar diferencias notables en su contribución al desarrollo sostenible. Por tanto, resulta necesario abordar la optimización en el diseño de sistemas energéticos no muy complejos, como primer paso a la optimización de la sostenibilidad de centrales eléctricas y otros sistemas complejos. Obviamente, cuanto mayor sea el uso del sistema energético a optimizar, mayor será el impacto de los resultados obtenidos.

En este sentido, los intercambiadores de calor son dispositivos de transferencia de calor entre fluidos empleados en múltiples industrias (Azad y Amidpour, 2011; Bahiraei et al., 2015; Bahiraei et al., 2017). En particular, los intercambiadores de carcasa y tubos son el tipo más empleado, dada su adaptabilidad a diferentes condiciones de operación

(Vasconcelos Segundo et al., 2017), su robustez y fiabilidad (Hadidi et al., 2013; Hadidi and Nazari, 2013), así como su relativamente simple proceso de manufactura (Vasconcelos Segundo et al., 2017).

La optimización de la sostenibilidad de intercambiadores de calor de carcasa y tubos puede generar un impacto positivo sobre Galicia, no sólo debido a su uso en múltiples industrias, sino también debido a la existencia de una empresa gallega especializada en su diseño y manufactura (Industrias Técnicas de Galicia, 2017).

Objetivos

Esta tesis está formada por cuatro publicaciones en las que se aborda la evaluación y la optimización de la sostenibilidad de sistemas energéticos.

Evaluación de la sostenibilidad de centrales eléctricas renovables y no renovables

El primer objetivo de esta tesis consiste en comparar la contribución al desarrollo sostenible de los tipos más importantes de centrales eléctricas, tanto renovables como no renovables, a lo largo de sus ciclos de vida.

Las publicaciones relacionadas con este primer objetivo son:

- **Artículo No. 1**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2015. Assessing the global sustainability of different electricity generation systems. Energy 89, 473-489. doi:10.1016/j.energy.2015.05.110.
- **Artículo No. 2**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2016. Probabilistic life-cycle cost analysis for renewable and non-renewable power plants. Energy 112, 774–787. doi:10.1016/j.energy.2016.06.098.
- **Artículo No. 3**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2017. Comparative analysis of direct employment generated by renewable and non-renewable power plants. Energy 9, 147–166. doi:10.1016/j.energy.2017.08.025.

La evaluación de la sostenibilidad de centrales eléctricas ha llamado la atención de un gran número de autores. Muchos estudios se centran en sistemas energéticos específicos de un determinado país o región. Otros trabajos abordan únicamente tecnologías muy concretas (potencia instalada, factor de capacidad, eficiencia, presión y temperatura de vapor, etc.) siendo minoritario el público al que van dirigidos.

Hasta dónde se ha podido saber, son pocos los estudios que consideran más de un caso concreto para cada tipo de central. Incluso en estos trabajos, se pueden apreciar ciertas deficiencias, normalmente asociadas a la ausencia de indicadores clave.

Por tanto, no existe en la literatura un modelo que proporcione una visión global de la sostenibilidad integral de los diferentes tipos de centrales eléctricas. El **Artículo No. 1** aporta varias contribuciones originales. Por un lado, presenta un modelo de evaluación que permite comparar los principales tipos de centrales respecto a su contribución al desarrollo sostenible, mediante un análisis detallado de los pilares económico, social y medioambiental. Por otro lado, dicho modelo está basado en el método MIVES, que nunca antes ha sido empleado en el sector energético con tal propósito.

El modelo se utilizó para evaluar diez tipos de centrales (cinco renovables y cinco no renovables). Para ello se emplearon veintisiete indicadores, lo que supera con creces el promedio de indicadores utilizados en la literatura existente.

Por otro lado, un análisis más detallado de los costes y de la generación de empleo fue abordado en los **Artículos No. 2** y **3**, respectivamente.

Respecto a los costes, también han sido muchos los autores que abordaron su estudio en el sector energético. Sin embargo, las conclusiones son de nuevo parecidas. Una cantidad considerable de los estudios se centran en el análisis de centrales concretas en un determinado país o región. Algunos autores fueron más allá, analizando distintos tipos de centrales dentro de un mismo país. Sin embargo, son pocos los estudios que consideran un conjunto amplio de centrales a escala global. Incluso en estos casos, el enfoque de la evaluación es predominantemente determinista.

No existe ningún estudio que proporcione una visión probabilista y global de los costes de las centrales renovables y no renovables más comunes. En este sentido, se puede decir que el **Artículo No. 2** realiza una contribución original doble. Por un lado, lleva a cabo un análisis probabilista de los costes de los diferentes tipos de centrales eléctricas a todo lo largo del mundo. Por otro, dicho estudio fue posible gracias al uso de dos modelos probabilistas, uno basado en el método MIVES-Monte Carlo y, el otro, en un enfoque de coste normalizado de electricidad combinado con simulación estocástica tipo Monte Carlo.

Ambos modelos se usaron para evaluar un total de dieciocho alternativas (cinco no renovables y el resto renovables), desde la etapa de extracción de combustible hasta el desmantelamiento de las instalaciones al término de la vida útil.

En términos de generación de empleo, muchos autores y muchas organizaciones de todo tipo han intentado profundizar en el análisis del sector energético. No obstante, todos los trabajos existentes tienen alcances similares a los comentados para la evaluación de la sostenibilidad y los costes. Es decir, no existe ningún trabajo que proporcione una visión global y probabilista de la generación de empleo directo por unidad de electricidad producida para los tipos de centrales más habituales. Por tanto, son varias las contribuciones originales aportadas por el **Artículo No. 3**. Por vez primera, en esta publicación se lleva a cabo un análisis probabilista de la creación de puestos de trabajo directos, tanto para centrales renovables como convencionales. Además, es la primera vez que se emplea un modelo analítico combinado con simulación Monte Carlo para tal propósito.

Con dicho modelo se evaluaron un total de diecinueve alternativas (cinco convencionales y catorce renovables), desde la etapa de extracción de combustible hasta el desmantelamiento de las mismas.

Los **Artículos No. 1**, **2** y **3** han servido para profundizar en el conocimiento y comprensión de la evaluación de la sostenibilidad de centrales eléctricas, proporcionando un análisis detallado tanto de la dimensión económica como de la generación de empleo. Por tanto, se puede afirmar que el primer objetivo de esta tesis se ha cumplido satisfactoriamente.

Optimización de la sostenibilidad de un intercambiador de calor de carcasa y tubos

El segundo objetivo de esta tesis consiste en el desarrollo de una nueva metodología integrada que permita optimizar la sostenibilidad de sistemas energéticos de todo tipo, así como su aplicación a un caso concreto, que en este caso ha sido el diseño de un intercambiador de carcasa y tubos.

La publicación asociada a este objetivo de la tesis es:

- **Artículo No. 4**: Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2018. Sustainability optimisation of shell and tube heat exchanger, using a new integrated methodology. En proceso de revisión.

Muchos autores han llevado a cabo estudios para optimizar el diseño de intercambiadores de calor de carcasa y tubos, adoptando diferentes funciones objetivo. La minimización de los costes es la más habitual.

Sin embargo, nunca nadie antes ha llevado a cabo un estudio en el que se optimice la sostenibilidad de un intercambiador de este tipo (ni de ningún otro). Son cuatro las aportaciones originales del **Artículo No. 4**. En primer lugar, se propone una metodología integrada para la optimización de la sostenibilidad de sistemas energéticos. La segunda aportación consiste en la aplicación de dicha metodología al diseño de un intercambiador de carcasa y tubos. En tercer lugar, dado que el índice de sostenibilidad se puede dividir en varios subíndices (cada uno de ellos asociados a un pilar de la sostenibilidad integral), es posible resolver este problema desde una óptica de optimización multiobjetivo. Por último, el método MIVES nunca antes ha sido aplicado con la finalidad de optimizar el diseño de un sistema energético.

El **Artículo No. 4** ha servido para cumplir de forma satisfactoria el segundo objetivo propuesto.

Metodología

En esta sección se resumen los aspectos más relevantes de las diferentes metodologías empleadas en este trabajo doctoral.

Método MIVES

MIVES (Modelo Integrado de Valor para una Evaluación Sostenible) es un método multicriterio de toma de decisiones determinista. Debido a sus características, presenta ciertas ventajas sobre otros métodos multicriterio habitualmente empleados en la literatura. MIVES se basa en el uso de árboles de requerimientos, funciones de valor y, opcionalmente, el proceso analítico jerárquico. Consta de siete fases (de la Cruz et al. 2014).

En la Fase A se define el problema a resolver. Tras ello, en la Fase B, se crea el árbol de requerimientos, es decir, un diagrama básico del modelo en la forma de esquema jerárquico. Dicho árbol contiene, de forma ordenada los aspectos concretos que se van evaluar (indicadores).

En el siguiente paso (Fase C), entran en juego las funciones de valor. Una función de valor no es más que una herramienta matemática que permite, entre otras cosas, transformar las diferentes unidades y magnitudes de los indicadores en un único parámetro adimensional, llamado valor, o índice de satisfacción; permiten también considerar no linealidades en la evaluación.

Los pesos o importancias relativas de los diferentes aspectos incluidos en el árbol de requerimientos son definidos en la Fase D. Esto se puede hacer de forma directa. Sin embargo, en casos de cierta complejidad se recomienda el uso del proceso analítico jerárquico (*Analytic Hierarchy Process*; AHP).

En la Fase E se definen las alternativas a evaluar. Dichas alternativas se evalúan en la siguiente fase (Fase F). Por último, en la Fase G, se toman las correspondientes decisiones.

MIVES Monte Carlo

La incertidumbre puede afectar a ciertas variables de las centrales eléctricas y de los sistemas energéticos. Sin embargo, MIVES es un modelo determinista. Por tanto, necesita ser combinado con una técnica que permita tener en cuenta la incertidumbre, como por ejemplo la simulación de tipo Monte Carlo (de la Cruz et al. 2014).

Por simulación de tipo Monte Carlo se entiende cualquier técnica numérica basada en el muestreo iterativo con números aleatorios o pseudo-aleatorios, que permite obtener una solución aproximada a un problema.

El método MIVES-Monte Carlo consta de nueve fases. En la Fase 1 se definen las variables que se van a tratar de forma probabilista (indicadores, pesos y funciones de valor pueden verse afectadas por la incertidumbre). El siguiente paso consiste en estimar los valores de entrada al modelo, tanto para las variables deterministas (Fase 2) como para las probabilistas (Fase 3).

Tras ello se lleva a cabo la simulación. Es decir, en la Fase 4, se generan los números pseudo-aleatorios. En la Fase 5 se realiza la evaluación mediante la aplicación del método MIVES. La Fase 6 consiste en repetir las dos fases anteriores hasta alcanzar la convergencia en los resultados.

Posteriormente a la simulación (Fase 7), se procede a la realización de un análisis estadístico de los resultados, con el objetivo de obtener la función de distribución resultante, así como los valores de los principales parámetros estadísticos (máximo, mínimo, media, entre otros).

En las Fases 8 y 9, respectivamente, el usuario debe interpretar los resultados y tomar decisiones; y recopilar los datos reales para aprender de ellos y mejorar en futuras evaluaciones.

Coste normalizado de electricidad

Existen múltiples métricas que permiten evaluar la factibilidad económica de una central eléctrica (valor actual neto, tasa interna de retorno, ratio coste-beneficio, entre otras). Sin embargo, la mayoría de estas técnicas necesitan calcular no sólo los costes, sino también los beneficios. Dichos beneficios suelen estar ligados a la política energética de cada país. Por tanto, si lo que se pretende es obtener una visión realista y objetiva del desempeño económico de los distintos tipos de centrales eléctricas, se debe emplear un método independiente de los beneficios, como el coste normalizado de electricidad (CNE).

El CNE sirve para evaluar el coste asociado a la producción de electricidad, en unidades monetarias, a todo lo largo del ciclo de vida de una central. De esta forma es posible realizar comparaciones entre alternativas con diferentes escalas de inversión y vida útil (Short et al., 1995).

Pese a sus ventajas, el CNE es una medida estática que aporta información sobre una de las múltiples situaciones que pueden ocurrir en la realidad. Es decir, los precios de los mercados son dinámicos (Yuan et al., 2014) y además, la incertidumbre juega un papel importante en los mismos. Por tanto, es necesario combinar esta métrica con una técnica, como la simulación e Monte Carlo, capaz de tener en cuenta la incertidumbre (de la Cruz et al. 2014).

Modelos analíticos

Existen dos tipos de técnicas empleadas para el cálculo de la generación de empleo en el sector energético: métodos de entradas y salidas, en inglés *input-output* (Blanco y Rodrigues, 2009; Henriques et al., 2016); y métodos analíticos (Lambert y Silva, 2012; Wei et al., 2010). Ambos presentan ventajas y desventajas.

Los métodos *input-output* modelan la economía como una interacción de bienes y servicios entre sectores industriales y consumidores. Por tanto, permiten calcular los puestos de trabajo directos, indirectos e inducidos, de forma neta. Ahora bien, para ello es necesario disponer de una gran cantidad de datos, bastante poco habituales en el caso de países en vías de desarrollo, e incluso de economías emergentes. Luego, en el contexto de esta tesis, la técnica *input-output* resultó ser inaplicable.

Los modelos analíticos son la otra opción. Suelen estar basados en el uso de bases de datos y hojas de cálculo. Son más sencillos y transparentes. Además, este tipo de modelos permiten introducir cambios y modificaciones de forma rápida y sencilla. A esto hay que añadir una menor necesidad de datos económicos. Ahora bien, pese a sus ventajas, el cálculo de esta técnica suele limitarse a los puestos de trabajo directos.

De nuevo resulta necesario combinar los modelos analíticos con una técnica, como Monte Carlo, capaz de considerar la incertidumbre, (de la Cruz et al. 2014).

Metodología integrada de optimización

Se basa en la creación de dos modelos. Un primer modelo, de diseño, que incluya todas las variables, ecuaciones y restricciones necesarias para una correcta definición del sistema que se pretende optimizar. Un segundo modelo, de evaluación, basado en el método MIVES. Una vez definidos ambos modelos es posible conectarlos, generando el modelo completo a optimizar. En otras palabras, las variables del primer modelo pueden adoptar diferentes valores. Cada conjunto de posibles valores está asociado a un diseño válido. Cada diseño tendrá sus características (costes, consumo de materiales, impactos medioambientales, etc.). Por tanto, las salidas del primer modelo pueden emplearse para calcular las entradas al modelo MIVES. Al mismo tiempo, este último modelo se emplea para estimar el índice de sostenibilidad asociado a cada diseño.

El siguiente paso consiste en llevar a cabo un proceso de simulación convencional o metaheurístico, para encontrar el diseño con mayor índice de sostenibilidad. Una primera posibilidad es aplicar Monte Carlo. Otra técnica sencilla es la búsqueda exhaustiva combinatoria, también llamada de fuerza bruta (Floudas y Pardalos, 2009).

Dado que es posible optimizar por separado cada uno de los pilares de la sostenibilidad integral, los algoritmos de optimización multiobjetivo también resultan ser apropiados. Este es el caso, por ejemplo, del Algoritmo Genético de Clasificación No Dominada II (Deb et al., 2002), que ha sido empleado en esta Tesis.

Resultados y discusión

En este apartado se resumen los resultados más relevantes de cada uno de los cuatro artículos que forman esta tesis.

Evaluación de la sostenibilidad de centrales eléctricas renovables y no renovables

La energía termosolar de alta temperatura obtuvo la mayor contribución al desarrollo sostenible, con resultados muy favorables en los pilares social y medioambiental. Pese a ello, su potencial es reducido en el caso particular de Galicia. De hecho, se espera que la expansión de este tipo de energía renovable tenga lugar mayoritariamente en las regiones situadas en el llamado cinturón solar.

A continuación, se encuentran la eólica terrestre y la solar fotovoltaica. Esta última también presenta un potencial reducido para Galicia, por las mismas razones que la termosolar. Sin embargo, las condiciones climatológicas y orográficas de Galicia sí son adecuadas para el desarrollo de la eólica. Tanto es así, que la potencia eólica instalada creció enormemente en los primeros años de este siglo, y se prevé un nuevo crecimiento para los próximos años.

La mini-hidráulica ocupa el cuarto puesto en términos de sostenibilidad integral. Por un lado, durante su operación apenas se necesita mano de obra. Por otro, la generación de empleo asociada a su construcción depende de la forma en la que ésta se lleve a cabo, pudiendo ser reducida. A esto hay que añadir la posibilidad de que ocurran accidentes con impactos considerables.

El quinto lugar lo ocupa la primera alternativa no renovable: la central térmica de gas natural, con una presencia considerable en el mix energético gallego. A cierta distancia le sigue la nuclear, que aparece como una opción muy atractiva, económicamente. Sin embargo, la producción de residuos radiactivos, así como las consecuencias catastróficas derivadas de posibles accidentes perjudican su puntuación global.

La biomasa resultó ser la alternativa renovable menos sostenible. Pese a que se puede considerar neutra en emisiones de CO_2, su contribución a otras categorías de impacto ambiental puede ser notable. Ahora bien, es bastante probable que la biomasa presente en Galicia una mayor contribución al desarrollo sostenible que la que tendría en otras regiones del mundo. El uso de este recurso serviría, entre otras cosas, para limpiar los montes, y ello reduciría el riesgo de plagas y, sobre todo, de incendio.

Por último, las centrales térmicas que emplean fuelóleo, carbón y lignito como combustible ocupan las tres últimas posiciones. Son, con diferencia, las centrales más contaminantes.

Pese a que los resultados obtenidos en el **Artículo No. 1** fueron analizados de forma crítica y validados mediante su comparación con los de la literatura existente, ciertos aspectos debían ser analizados en mayor detalle. Esto dió lugar a los **Artículos Nos. 2** y **3**.

El **Artículo No. 2** profundiza en el análisis de la dimensión económica de las centrales eléctricas. Todas las centrales no renovables obtuvieron un coste normalizado de electricidad modal comprendido en el intervalo [50, 100) €/MWh. Las energías renovables obtuvieron valores mayores, con la excepción de la eólica terrestre, que se situó a la misma altura que las mejores centrales convencionales.

De hecho, las centrales térmicas de carbón y lignito, así como las nucleares, obtuvieron los mejores resultados, seguidas de la eólica terrestre. Las centrales térmicas de gas natural y fuelóleo se situaron a continuación, penalizadas por no funcionar siempre en régimen de carga base.

La biomasa resultó ser una de las opciones renovables más atractivas en el ámbito económico, lo que contradice ligeramente los resultados obtenidos en el primero de los artículos. Esto se debe a algunas desventajas metodológicas que presenta MIVES, bajo ciertas condiciones. El lector puede encontrar más información al respecto en el **Artículo No. 2**. La mini-hidráulica obtuvo un intervalo amplio de posibles resultados, siendo capaz de lo mejor y de lo peor.

La fotovoltaica y la eólica marina fueron las siguientes alternativas en la clasificación. Bajo ciertas condiciones, sus costes normalizados de electricidad (CNE) pueden alcanzar valores muy altos. La energía termosolar de alta temperatura, con y sin hibridación, obtuvo resultados intermedios.

Las centrales mareomotrices de barrera obtuvieron resultados competitivos respecto a otras opciones renovables. Ahora bien, sus impactos medioambientales frenan su expansión. Por otro lado, tanto la energía mareomotriz de corriente, como la undimotriz, presentaron los peores resultados, debido a que todavía se encuentran en una fase temprana de desarrollo.

En otro orden de cosas, en el **Artículo No. 3** se profundiza en el análisis de la generación de empleo directo por unidad de electricidad producida. Las centrales térmicas de carbón obtuvieron resultados intermedios; esto puede parecer sorprendente, dada la existencia de una etapa de extracción y minería. Sin embargo, el elevado grado de automatización reduce considerablemente la necesidad de mano de obra. Las centrales que emplean lignito obtuvieron resultados ligeramente superiores, derivados del menor poder calorífico de este combustible.

En la misma línea, la creación de puestos de trabajo directos de las centrales de gas natural y fuelóleo también resultaron estar lejos de las alternativas más atractivas.

La energía nuclear requiere mucha mano de obra durante las etapas de construcción, instalación y desmantelamiento. Sin embargo, son las centrales no renovables menos intensivas en consumo de combustible. A esto hay que añadir que, por razones técnicas, sólo trabajan en carga base. Por lo tanto, su generación de empleo por unidad de electricidad resulta ser baja.

La eólica terrestre presentó resultados alejados de las mejores opciones, consecuencia directa de su elevada madurez tecnológica. Lógicamente, la eólica marina precisa una mayor cantidad de mano de obra, aunque sólo sea como consecuencia de la necesidad de personal asociada a las actividades que no tienen lugar en tierra.

La solar fotovoltaica obtuvo los mejores resultados, seguida de cerca por la biomasa, la mini-hidráulica y la termosolar de alta temperatura.

La mareomotriz de barrera y la gran-hidráulica presentaron la menor generación de empleo directo. Esto se debe a que no se consideró la etapa de desmantelamiento ya que, debido a su complejidad técnica, se evita siempre que sea posible.

La mareomotriz de corriente y la undimotriz obtuvieron tasas de creación de empleo elevadas. Resultado lógico, ya que se trata de un sector todavía emergente.

Optimización de la sostenibilidad de un intercambiador de calor de carcasa y tubos

En el **Artículo No. 4** se lleva a cabo la optimización de la sostenibilidad de un intercambiador de carcasa y tubos para sub-enfriar metanol condensado, desde 368.15 K (95 ºC) hasta 313.15 K (40 ºC), utilizando agua salobre como refrigerante, con un incremento de temperatura de 298.15 K (25 ºC) a 313.15 K (40 ºC).

Se emplearon las tres técnicas de optimización descritas en el apartado de metodología. El índice de sostenibilidad obtenido mediante la búsqueda por fuerza bruta resultó ser el más elevado. Sin embargo, las tres técnicas proporcionan resultados muy parecidos.

El mejor diseño presentó un índice de sostenibilidad de 0.7941, siendo 0 y 1 los límites pésimo y óptimo, respectivamente (lo cual no quiere decir que sea factible llegar a 1). De hecho, el peor diseño válido resultó tener un índice de sostenibilidad de 0.2791, siendo la media de todos los diseños factibles de 0.5215. Esto proporciona una idea del potencial que presenta la metodología integrada para optimizar el diseño de un sistema energético que se ha propuesto y empleado en esta Tesis.

Conclusiones

En este apartado se resumen las principales conclusiones de este trabajo doctoral.

Evaluación de la sostenibilidad de centrales eléctricas renovables y no renovables

El **Artículo No. 1** aborda satisfactoriamente la evaluación de la sostenibilidad de centrales eléctricas, tanto renovables como no renovables, mediante la consideración de los pilares clásicos de la sostenibilidad, en profundidad.

La conclusión principal es que existe una gran diferencia en la contribución al desarrollo sostenible entre las dos primeras opciones (termosolar de alta temperatura y eólica terrestre) y las tres últimas alternativas (térmicas de fuelóleo, carbón y lignito).

En general, las energías renovables presentaron mayores índices de sostenibilidad, con la excepción de la biomasa.

A nivel metodológico se ha demostrado que MIVES es una técnica válida para su aplicación en la evaluación de la sostenibilidad de centrales eléctricas.

En el **Artículo No. 2** se analizan de forma conveniente los costes de ciclo de vida de centrales eléctricas tanto renovables como convencionales.

De los resultados obtenidos se puede concluir que la incertidumbre juega un papel muy importante a la hora de evaluar y comparar distintos tipos de centrales desde la óptica económica. Las centrales convencionales aparecieron como las opciones más competitivas. Sin embargo, algunas renovables (eólica terrestre, biomasa, mini-hidráulica e incluso las alternativas solares) también pueden ser competitivas bajo ciertas condiciones, incluso llegando a superar a algunas centrales no renovables.

En lo metodológico, se ha demostrado que MIVES puede presentar ciertas desventajas que requieren de un análisis crítico de los resultados. El lector puede encontrar más información al respecto en el **Artículo No. 2**.

El **Artículo No. 3** contribuye de forma satisfactoria al cumplimiento del primer objetivo de esta tesis, mediante un análisis probabilista detallado de la generación de empleo directo en el sector energético.

La conclusión general es que, de nuevo, la incertidumbre juega aquí un papel importante. Los resultados muestran que algunas renovables (fotovoltaica, biomasa, mini-hidráulica, mareomotriz de corriente, undimotriz) siguen siendo las opciones más atractivas a nivel de creación de puestos de trabajo directos. Pese a ello, las centrales convencionales pueden competir con sus homólogas renovables, bajo ciertas condiciones.

En lo metodológico, este estudio confirmó que es posible aplicar con éxito modelos analíticos a nivel nacional e internacional.

Optimización de la sostenibilidad de un intercambiador de calor de carcasa y tubos

En el **Artículo No. 4** se aborda la optimización de la sostenibilidad de un intercambiar de calor de carcasa y tubos mediante la aplicación de una nueva metodología integrada.

La conclusión principal es que la metodología empleada resulta de gran ayuda a la hora de seleccionar el diseño más sostenible de entre todos los posibles para una determinada aplicación. De hecho, para el caso de estudio analizado, los diseños presentaron un índice de sostenibilidad que varió entre 0.2791 (pésimo) y 0.7941 (óptimo, o sub-óptimo).

Por tanto, se ha demostrado que, incluso bajo las peores condiciones posibles, vale la pena buscar el diseño más sostenible, ya que la contribución al mismo puede variar significativamente.

Futuros desarrollos

Parte de lo incluido en este epígrafe ya se encuentra terminado. Sin embargo, no ha sido incorporado a la presente tesis por no encontrarse en forma de artículo de investigación, publicado o enviado para ser publicado. Para más información, el lector puede consultar el Apéndice B.

Evaluación de la sostenibilidad de centrales eléctricas renovables y no renovables

El modelo presentado en el **Artículo No. 1** puede ser mejorado de dos formas diferentes. Por un lado, debe considerarse la incertidumbre mediante, por ejemplo, la aplicación de simulación tipo Monte Carlo. Por otro, debe estudiarse la posibilidad de incorporar nuevos indicadores, así como un cuarto pilar de la sostenibilidad: técnico o funcional.

Respecto a la dimensión económica, se debe contemplar la posibilidad de incluir nuevos indicadores como, por ejemplo, los que permitan medir los costes asociados a accidentes o desastres naturales.

En cuanto a la generación de empleo, es necesario ir más allá de un análisis meramente numérico, considerando aspectos tales como las condiciones laborales, los derechos de los trabajadores, salarios, etc.

Optimización de la sostenibilidad de un intercambiador de calor de carcasa y tubos

El modelo MIVES incluido en el **Artículo No. 4** puede ser aumentado, mediante la incorporación de nuevos indicadores que, entre otras cosas, hagan posible la evaluación de todos los componentes del intercambiador (incluyendo la manufactura).

Metodológicamente, otras técnicas de optimización, tales como el recocido simulado, la búsqueda tabú, u otros algoritmos genéticos, pueden ser incorporados a la metodología propuesta.

Adicionalmente podría emplearse dicha metodología para la optimización de la sostenibilidad de sistemas energéticos de mayor envergadura, como una central eléctrica en su totalidad. Como punto de partida, se podría resolver el mismo caso de estudio pero, esta vez, aumentando el número de variables.