

Energy Policy Analysis

Energy planning requires the study of the interactions between the economy (at national or regional levels), the energy sector and the related impacts on the environment. Many countries do not hold indigenous energy resources becoming highly dependent on primary energy imports. In such cases, an increase of energy consumption which greatly relies on fossil fuels is frequently interweaved with economic growth, also leading to the exhaustion of finite resources and to Greenhouse Gas (GHG) emissions. To sum up, negative effects on economic growth and social welfare might be prompted as an outcome of energy and environmental policies. Henceforth, other evaluation facets besides economic concerns such as environmental and social welfare impacts should be explicitly considered in the appraisal of the merits of energy plans and policies to address energy problems in a societal perspective (Antunes and Henriques, 2016).

Thus, the assessment of the trade-offs between economic growth, energy demand/supply, as well as their corresponding environmental and social effects is particularly relevant for energy planners and decision-makers (DM) through the use of reliable tools for supporting the process of energy policy decision-making. In this context, the use of multiobjective programming models and methods combined with Input-Output (IO) analysis can be particularly appropriate for assisting in the process of Economy-Energy-Environmental (E3) policy design (Oliveira et al., 2016).

IO analysis is a top-down approach which can be intertwined with environmental satellite accounts provided by national statistical offices, allowing broad impact coverage of all sectors directly and indirectly involved with the energy sector. Furthermore, IO has influenced the outset of linear programming (LP) (Vogstad, 2009) and it may be considered as a simple particular case of LP (Dorfman et al. 1958). The combined use of the IO methodology with LP models allows attaining value-added information, which would not be possible to achieve with the isolated use of both techniques. Inter/intra-sector relations entrenched in IO analysis allow obtaining the production possibility frontier. LP models enable selecting the level of activities which optimize a given objective function, satisfying the production sector relations imposed by IO analysis. Additionally, IO MOLP models allow assessing different efficient possibilities of production (i.e. output levels for each activity sector for which there is no other feasible solution that allows improving the value of a given objective function without worsening the value of, at least, other objective function) that can be reconciled with the competing axes of evaluation intrinsically at stake (Oliveira et al., 2016).

Strategic Problems

LP formulations of IO systems have been a normal part of standard texts since the 1960s (Ten Raa, 1994). The first IO LP models developed only addressed the economic system, but after the first oil crisis energy-environmental planning models started to play a prominent role.

IO analysis allows establishing an overarching framework to model the interactions between the whole economy and the energy sector, thus identifying the energy required for the provision of goods and services in an economy and also quantifying the corresponding pollutant emissions. Several indicators (either modelled as constraints or as objective functions) are obtainable with the application of IO LP/MOLP models specifically devoted to energy planning:

Economic

- Gross Domestic Product (GDP);
- Gross Regional Product (GRP);
- Gross Value of Production (GVP);
- Output levels;
- Private consumption;
- Balance of payments;
- Foreign-trade-balance;
- Gross value added;
- Public deficit;
- Production capacity;
- Exports and imports;
- Cost of the energy system;

- Employment;

Energy

- Energy imports;
- Energy use;
- Storage capacity;
- Security stocks for hydrocarbons;
- Wastes with energetic use;
- Efficient energy use;

Environmental

- GHG emissions (based on CO₂, N₂O and CH₄);
- Acidifying substance emissions (based on SO₂, NO_x and NH₃);
- Environmental discharges not related to fuel combustion;
- Wastes produced.

Integrated energy planning models

Integrated energy planning (IEP) strives to account for the relevant strategic elements of the energy value-chain at a national level/regional level. IEP is intrinsically a multiobjective problem and when sustained by IO MOLP modelling tools, distinct alternative energy pathways can be assessed which can be consistent with different policy options. The solutions obtained help DMs to assess how energy requirements can be reduced without harming economic growth and socioeconomic development, allowing to understand the relationship (trade-off) between energy supply/demand and economic development/growth and corresponding environmental impacts.

IO MOLP models support IEP and provide help in the design of energy policies, namely guiding:

- the proposal of balanced energy policy configurations;
- the selection of appropriate technologies to meet energy demand;
- the suggestion of strategies to appraise the impacts of energy supply shortages/disruptions in an integrated manner;
- the development of procedures to assess the effects of nuclear power plant accidents, trade embargoes, and international conflicts, among others;
- reallocation of production problems;
- biomass production optimization;
- energy import resilience;
- energy-economic recovery resilience of an economy;
- energy efficiency planning.

Regional energy planning

Since the national energy supply/demand structure cannot reflect regional characteristics, regional energy planning is particularly relevant because it allows capturing each region's specificities, before being articulated with national energy planning.

IEP models

Balanced regional policy configurations can be obtained by means of IO MOLP models. With the foregoing in mind, Moulik et al. (1992) presented a macro-level energy model aimed at minimizing the total cost of the energy system and its application to energy planning for three states in India (Gujarat, Kerala and Rajasthan). The methodology considers a reference energy system, an expanded IO table with disaggregated energy sectors and an LP model combined with a scenario analysis approach.

Cho (1999) developed a model which includes the minimization of energy consumption and pollution, and the maximization of employment, being subject to the restriction of the range of outputs for twelve individual sectors considered, regarding the total output level of the Chungbuk economy. The impact multipliers (employment, pollution and energy consumption) are calculated and then combined with decision variables to form the objective functions of the MOLP model. The results of the model are able to illustrate how the regional production structure should be reorganized in order to become a more balanced one.

Assessment of energy shortage impacts

The assessment of energy shortage impacts has been formulated as an LP problem in Leung and Hsu (1984), where an energy flow matrix for Hawaii is built and the 1977 Hawaii IO table is used to evaluate each sector's direct energy intensity and total energy intensities.

The authors calculate shadow prices for different levels of gasoline availability with the use of an LP model and show that the solution thus obtained provides an efficient distribution of energy resources to various industry sectors during energy shortages.

IEP models under dynamic assumptions

Leontief (1985) suggested the dynamic IO model where a new matrix describing the capital resources is considered, aimed at distinguishing different technological structures in different time frames. With this modelling formulation it is possible to account for the growth potential of an economy, since the final demand vector of the static IO model is replaced by a stock's coefficient matrix that is then multiplied by the anticipated increase of the output level between the present year and the following year. This new set of differential equations represents the dynamic relations of the IO model, allowing for the description and analysis of the economic growth process (Leontief, 1985). Based on this type of approach Zou et al. (2014) applied an LP dynamic IO model considering the case of renewable energy industries, as well as the environmental policy instrument of emission taxes. In addition to exploring the relationships among Beijing's renewable energy, economy and environment, the model analyses the future trends of the economy and GHG intensity from 2010 to 2025. The objective function is the maximization of the total GRP from 2010 to 2025, being subject to constraints regarding material flow balance, value flow balance, electricity supply-demand balance, investment-savings balance and GHG emissions.

James et al. (1986) suggested the combination of the IO model with a dynamic energy technology optimization model to compute the change in total energy demand and technological mix. The authors were able to identify through the use of the model part of the economic repercussions of technological change and inter-fuel substitution.

National energy planning

IEP models at the national level, explicitly incorporating the interactions of the energy system with the economy have been developed based on IO MOLP.

IEP models

Hsu et al. (1987) use the bicriterion NISE method for assessing the trade-offs between GDP and energy use in Taiwan. The solutions obtained represent simulated scenarios of aggressive, moderate and conservative policy alternatives. The evaluation of the outcomes is mainly centered on the economic performances resulting from the different policy alternatives and the energy requirements for supporting that performances.

The impacts of the electricity power industry can also be assessed by coupling IO with goal programming models. A goal programming model has been suggested in Amagai and Leung (1991) to analyse the trade-offs among economic (generation cost minimization) and environmental (CO₂ emissions minimization) objectives for the year 2000 in Japan's electricity power industry, which allows discussing the nature of the trade-off curve and the extent of power generation by source.

Antunes et al. (2002) consider the TRIMAP interactive environment to analyse the interactions of the energy system with the economy in Portugal. Another version of this model with six objective functions (maximization of GDP, private consumption, self-power generation and employment, and minimization of energy imports and CO₂ emissions) was proposed in Oliveira and Antunes (2002) and solutions were obtained using the interactive STEM method. In Oliveira and Antunes (2004) an interactive procedure to obtain solutions is employed based on a min-max scalarizing function associated with reference points, which are displaced according to the DM's preferences expressed through average annual growth rates. The objective functions considered in the model are: minimisation of acidification potential, maximisation of self-power generation, maximisation of employment, maximisation of GDP, and minimisation of energy imports.

Kravtsov and Pashkevich (2004) suggested a three-objective LP model aimed at maximizing the GDP, minimizing the use of fuel and energy resources, and maximizing the foreign-trade balance. Solutions were computed using a weighted sum approach, with information on Belarus over the 1996–2000 period.

Hristu-Varsakelis et al. (2012) optimized production in the Greek economy, under constraints relating to energy use, final demand, GHG emissions and solid waste. The effects on the maximum attainable GVP when imposing various pollution abatement targets were considered using empirical data. The results obtained quantify those effects as well as the magnitude of economic sacrifices required to achieve environmental goals, in a series of policy scenarios of practical importance. Because air pollution and solid waste are not produced independently of one another, the settings in which it is meaningful to institute a separate policy for mitigating each pollutant versus those in which only one pollutant needs to be actively addressed are identified. The scenarios considered represent a range of options that could be available to policy makers, depending on the country's international commitments and the effects on economic and environmental variables.

Cristóbal (2012) proposed an IO MOLP model combined with goal programming to assess economic goals (output levels), social goals (labour requirements), energy goals (reduction of coal requirements by 5%), environmental goals (reduction of total emissions of GHG and waste emissions by 10%). Solutions are obtained by considering the minimization of the total deviations from the goals.

Carvalho et al. (2016a) proposed a hybrid IO MOLP model applied to the Brazilian economic system aimed at assessing the trade-offs associated with the maximization of GDP and the minimization of the total energy consumption and GHG emissions, considering the timeframe of 2017. The TRIMAP interactive environment was employed to grasp the trade-offs between these objective functions.

Assessment of economic or political crises

The quantitative effects of economic or political crises can be assessed with IO MOLP models. Examples of such crises are nuclear power plant accidents, trade embargoes, and international conflicts. Kananen et al. (1990) showed how a visual, interactive, dynamic MOLP decision support system can be effectively used with this aim in the Finnish economy. The IO MOLP model considers as objectives the maximization of private consumption, trade deficit and employment, and the minimization of the overall energy consumption.

Models devoted to reallocation of production problems

The reallocation of production problem can be formulated as a constrained optimization problem. Taking Greece as a case study, Hirstu-Varsakelis et al. (2010) considered the reallocation problem on a sector-by-sector basis, in order to meet overall demand constraints and GHG Kyoto emissions targets. The authors take into account the Greek environmental IO matrix for 2005, the amount of energy utilized and pollution reduction options. The model is aimed at maximizing total GVP subject to upper bounds on energy use and pollution, lower and upper bounds on production, and lower bounds on the GVP of every activity sector.

Models devoted to biomass production optimization

IO MOLP models can be adjusted to include several alternative technologies. In this case, the LP formulation is able to handle the representation of alternative technologies (Vogstad 2009). This hybrid approach of linking detailed models with aggregated, economy-wide models is the current focus of research in Life Cycle Assessment (LCA). Following this approach, Carvalho et al. (2016b) developed a hybrid IO framework coupled with LCA based estimates for two sugarcane cultivation systems, two first-generation and eight second-generation technology systems for bioethanol production scenarios. The integrated- or country-based assessment of the whole economic system has accompanied the process design and process-based analysis, supporting the identification of direct and indirect effects that can counterweight the benefits. The consideration of direct and indirect effects on the whole economic system is critical in policies and technological choices for prospective bioethanol production, since positive direct effects of first-generation and second-generation plants can be offset by indirect impacts on other sectors.

Energy import resilience

Energy import shortages may occur in various importing sectors and most of the times cannot be foreseen in advance. Models aimed at addressing energy import resilience can be used to simulate the impact of specified energy import losses on the sectoral production levels, and consequently, the final supply-demand balance. In this context, He et al. (2015) developed an IO LP model that focuses on the connection

between energy imports, industrial production technologies and capacities. The main value added of rests on the possibility offered by the proposed model of appraising the worst-case scenario impact over a family of (possibly in finite) import loss scenarios. The impact of an energy import loss on the economy is the amount of final demands of goods that cannot be balanced by the given supply and production in the short run. An energy import resilience indicator is then defined, which essentially assesses the highest level of energy import loss possible to the economy. The methodological framework is also extended in order to encompass production capacity designs that allow reaching the maximum possible energy import resilience of a given IO structure.

Energy-economic recovery resilience of an economy

He et al. (2017) proposed an IO LP to appraise the energy-economic recovery resilience of an economy by studying the interactions between energy production disruption, impacts on sectoral production and demands, and post-disruption recovery exertions. The developed model evaluates the minimum level of recovery investments necessary to reinstate production levels so that total economic impacts are tolerable over a specified post-disruption extent. It is presumed that disruptions are uncertain and can take place at different sectors and possibly simultaneously. The optimization model is then solved using a cutting plane method which involves computing a small sequence of mixed integer programming problems of reasonable dimensions. Taking China's 2012 IO data as a case study, the study illustrates the model's ability to unravel vital inter-sectoral dependencies at different disruption levels. DMs become acquainted with relevant information in regarding the appraisal and enhancement of the energy-economic resilience in a comprehensive manner.

IEP under uncertainty

The accurate specification of the coefficients of optimization models is a challenging endeavour in most real world problems since sometimes there is not enough information available. Moreover, the technical coefficients of the IO matrix may be subject to a considerable level of uncertainty. Uncertainty handling in the outline of IO analysis may be essentially based on three different approaches: the probabilistic approach, in which the probabilistic distribution functions associated with all the coefficients are presumably well known (*e.g.* West, 1986; Ten Raa and Steel, 1994); the interval approach (unknown but bounded coefficients), where the upper and lower bounds of the coefficients are considered without being associated with a structure of possibilities or probabilities (*e.g.* Jerrel, 1996; Jerrel, 1997); and the fuzzy (or possibilistic) approach, in which membership functions are assigned to all uncertain coefficients (*e.g.* Buckley, 1989). Therefore, IO LP/IO MOLP models explicitly handling uncertainty of the model coefficients have arisen in scientific literature.

Borges and Antunes (2003) proposed an IO MOLP model with fuzzy coefficients in the objective functions and fuzzy right hand sides of the constraints for E3 planning in Portugal. Interactive techniques were used to perform the decomposition of the parametric (weight) diagram into indifference solutions corresponding to basic non-dominated solutions.

Oliveira and Antunes (2011, 2012) have considered all IO MOLP model coefficients as intervals, then conveying information regarding the robustness of non-dominated solutions (that is, solutions that achieve desired levels for the objective functions across a set of plausible scenarios) under a more optimistic or pessimistic DM's stance. With the introduction of (direct and indirect) employment multipliers, this IO structure has been used to extend the interval MOLP to assess the trade-offs between economic growth (GDP), social welfare (employment), and electricity generation based on renewable energy sources (Oliveira et al., 2013).

Models devoted to biomass production optimization

Case studies based on electricity generation from biomass and ethanol production can be assessed to illustrate how the model determines optimal production levels of feedstock within each region, as well as optimal levels of trade between regions and imports from external sources. With this purpose Tan et al. (2012) presented a multi-regional fuzzy IO model to optimize biomass production and trade under resource availability and environmental footprint constraints. Uncertainty was only considered on the upper or lower bounds of the constraints.

Models devoted to energy efficiency planning

The introduction of a bottom-up approach into an IO MOLP model enables extending its application to the assessment of energy efficiency measures. This methodological framework combined with mathematical interval programming tools was followed in Oliveira et al. (2015) to account for investment options aimed at improving the thermal properties of the building envelope (e.g., the insulation of external walls and roof, and the replacement of window frames and window glazing) in Portugal. The objective functions are the maximization of GDP, the building renovation investment, and the overall level of employment, being subject to several economic and environmental constraints.

Challenges of IEP planning with MOLP IO models

The main difficulty found in the studies carried out with these models rests on the availability of statistical information. In fact, the application of the IO approach in the framework of electricity generation can be a complex and challenging task since published IO tables do not allow assessing the environmental impacts that are likely generated from an increase in the demand from electricity generation from renewable energy and/or for conventional energy, but only the impact of an increase in demand for electricity in general. Published IO tables consider a single aggregated electricity sector, where generation, transmission, distribution and supply activities related to the production and use of electricity are included. Therefore, it is important to disentangle the different possible ways to tackle the disaggregation of the electricity sector.

Despite the typical limitations found when considering this type of approach, the power of IO analysis rests upon its capacity of depicting the technology of a country or region with enough accuracy to allow performing a real empirical study. In addition, IO analysis is a flexible tool that can be applied to a wide variety of problems, which can be used to modelling complex systems of economic and physical interrelations. In reality, IO analysis enables assessing any type of environmental burden caused by changes in the output of economic sectors once reliable data is used.

A broad range of (economic, social, energy and environmental) indicators according to coefficient scenarios and output levels attained for the activity sectors (industries) might thus be obtained with IO LP/MOLP models, which provide a useful planning and prospective analysis tool.

A major drawback usually mentioned in scientific literature relates to the static nature of the IO traditional matrix. However, the IO MOLP framework has evolved, explicitly encompassing the uncertainty handling of the model's coefficients, helping to overcome this particular limitation. This modelling approach could, nevertheless, benefit from the development of a dynamic, multi-period variant, relying on the integration of time-dependent technical parameters to account for technological learning curves and yield improvements, as well as incorporate game theoretical principles to accurately reflect the typical multi-agent's nature of the problem.

Another possibility for further enriching this modelling framework would be the development of tools for obtaining solutions considering the interaction with multiple planners/DMs with potentially conflicting views. The involvement of distinct stake-holders would bring new insights into the decision-making process at all stages, from model's definition to the evaluation of solutions.

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