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Village-scale Multi-Energy system modelling tools: a review and critical analysis

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Dai un pesce a un uomo e
lo nutrirai per un giorno.
Insegnagli a pescare e
lo nutrirai per tutta la vita.

\- Confucio -

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Abstract

Tools for energy systems modelling and planning are essential to ensure technical and economic sizing. Nowadays, a wide range of models aimed at this objective, characterized by different purposes and priorities, exist. It is however necessary to choose the model best suited to specific needs and ends in order to guarantee an effective and easy sizing of the energy system, otherwise negative consequences on cost and efficiency could arise. This planning tools can differ from each other for the type of analysis performed, the geographical area considered, the goals determined, the energy sectors and technologies included.

Nevertheless, the majority of the most widespread tools, and of which more information is known, addresses its attention primarily on large scale energy system modelling and covers mainly electrical demand, neglecting important energy needs such as heating and cooking. Moreover, the increasing interest towards the disadvantageous energy conditions of developing countries makes necessary the knowledge and the diffusion of new models based on smaller energy system scales and which also include sectors other than electric one. In fact, the population of these countries lives mainly in small villages located in rural areas where access to energy is limited and the primary source for cooking, heating and lighting is the harmful and polluting biomass. Among the possible solution in such contests, the most suitable from an economic and efficiency point of view is the diffusion of autonomous *off-grid* systems: they comprehend stand-alone systems for only one consumer and micro-grids in which more than one consumer and energy sources are included.

As a matter of fact, the present thesis work aims to carry out a literature review of the existing models, excluding all those which are not suitable for the optimization of rural energy systems and therefore focusing the attention on the tools with ideal features for modelling multi-energy systems in isolated areas. These tools should also allow possible further integrations and enable the aggregation of more multi-energy systems. A detailed analysis of properties and of main information, a comparative analysis and a final consideration about benefits and drawbacks of each tools is performed. Moreover, it is highlighted which tools could be the most suitable for the above-mentioned purposes.

Keywords: Energy Modelling Tools, Multi-Energy Systems, Rural Areas, Energy Access, Open Source, Literature Analysis.

Sommario

Gli strumenti per la modellizzazione e la pianificazione dei sistemi energetici sono essenziali per garantire un corretto dimensionamento tecnico ed economico. Attualmente, in letteratura esiste una grande varietà di modelli rivolti a questo intento, caratterizzati da diversi scopi e proprietà. Tuttavia è necessario scegliere il modello più adatto alle specifiche esigenze e finalità in modo da garantire un valido e agevole dimensionamento del sistema energetico, altrimenti si potrebbero avere delle conseguenze negative sui costi e sull'efficienza del sistema. Questi strumenti di pianificazione posso differire per esempio per il tipo di analisi svolta, l'area geografica considerata, gli obiettivi fissati, le tecnologie e i settori energetici inclusi.

Ciononostante, la maggior parte degli strumenti attuali più diffusi e di cui si conoscono più informazioni sono rivolti principalmente alla modellizzazione di sistemi energetici su ampia scala e alla copertura della domanda elettrica, tralasciando importanti bisogni energetici come il riscaldamento o la cottura di alimenti. Inoltre, il crescente interesse verso le sfavorevoli condizioni energetiche dei paesi in via di sviluppo rende necessaria la conoscenza e la diffusione di nuovi modelli basati su scale energetiche più piccole e che includano anche settori diversi da quello elettrico. Infatti la popolazione di questi paesi vive principalmente in piccoli villaggi situati in zone rurali dove l'accesso all'energia è alquanto ridotto e la fonte primaria per cuocere gli alimenti, di calore e di illuminazione è la biomassa, nociva e inquinante. Tra le soluzioni possibili in tali contesti, la più adatta dal punto di vista dei costi e di efficienza è la diffusione di sistemi *off-grid* autonomi: essi includono sistemi indipendenti per un solo tipo di consumatore o micro reti che comprendono più consumatori e risorse energetiche.

Il presente lavoro di tesi ha difatti lo scopo di effettuare una revisione dei modelli esistenti in letteratura, scartando tutti quelli che non sono adatti a ottimizzare sistemi energetici in contesti rurali e focalizzando l'attenzione quindi su tutti quegli strumenti che presentano caratteristiche ideali per la modellizzazione di sistemi multi energetici in aree isolate, che consentano anche possibili future integrazioni di moduli, per esempio, e che permettano aggregazione di più sistemi multi energetici. Di tali strumenti è stata eseguita una descrizione dettagliata delle proprietà e delle informazioni principali, un'analisi comparativa e una considerazione finale atta a evidenziare i vantaggi e gli svantaggi di ogni modello, specificando quali tra essi potrebbero essere i più adatti agli scopi sopra citati.

Parole chiave: Strumenti di Modellizzazione Energetica, Sistemi Multi-Energetici, Aree Rurali, Accesso all'Energia, Open Source, Analisi della Letteratura.

Introduction

On the entry of the new millennium, energy has become one of the major issues discussed worldwide: global concerns such as climate change, energy security, renewable energies and energy efficiency are now considered the main priorities to address by most governments. Indeed, in the past the attention was primarily focuses only on costs and energy security. The new situation is also a consequence of the global financial crisis of 2007, which has pushed some developed countries towards policies focusing on reducing energy dependency [1].

Moreover, more and more attention is paid to people in the world who do not have access to energy: according to IEA (International Energy Agency) [2] 1.1 billion people, ca 15% of the global population, still remain without access to electricity and approximately 2.8 billion people, ca the 40% of the global population, still continue to rely upon harmful fuels such a solid biomass and animal dung as their primary cooking fuel. These people mainly live in developing countries and, in particular, in rural areas, where deployment costs of the national electric grid are prohibitive (**Figure 0.1**).

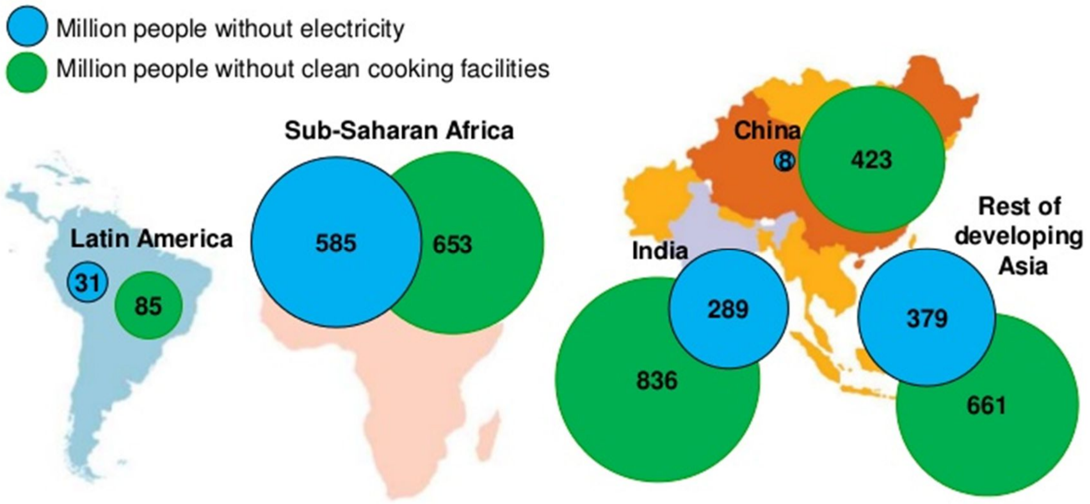


Figure 0.1 People in the world without access to energy. Source: wbcsd development, IEA.

In order to try to solve all these new problems, to guarantee all these renewed priorities and to provide access to energy in an efficient techno-economic way in rural areas, good energy planning is required. However, it can only take place when good energy models are used. Today, a wide range of modelling tools exists, with different aims and characteristics. Nevertheless, most of existing tools focuses only on large energy systems and on electrical services, neglecting other important energy needs such as heating and cooking. It is important to choose the right type of model on the basis of the specific purposes, otherwise a wrong planning will be obtained with consequences mainly on costs and efficiency.

For these reasons, this work aims to provide a comprehensive review of all existing tools, focusing on the ones best suitable for properly and efficiently modelling multi-energy systems in rural areas and best suited for providing both electrical and thermal load and for further integrations of modules or other features.

The characteristics considered the most appropriate by this thesis for rural energy planning tools are:

- small scale of the energy system considered;
- bottom up approach;
- free availability to guarantee accessibility and affordability;
- open source code to ensure adaptability, transparency , knowledge transfer, capacity building and empowerment. It is essential not only provide the correct energy system, but also to involve, inform and train local people in order to improve their social and political situation;
- micro-grids and stand-alone application possibility: most of the times these rural areas are far from the existing network. Therefore, the extension of the grid could be too expensive and complex;
- presence of renewable-based and conventional fuels-based technologies: to exploit local resources, to reduce the energy dependency and to avoid outages;
- multi-sectorial and synergies between sectors in order to consider both electrical and thermal load;
- short scenario timeframe: in these areas everything is constantly changing.

In the following sections, the issue concerning the importance of access to energy and the energy modelling are discussed. In particular:

- *Chapter 1* is dedicated to highlight the importance of energy access in developing countries from an economic, social and environmental development point of view. Moreover, it focuses on the need for energy models suitable for off-grid energy system planning, highlighting the characteristics that they should have and the differences with the tools already used for developed countries energy systems;
- in C*hapter 2* the methodology adopted for finding and classifying all the found tools and for evaluating the ones most suited for rural planning is explained;
- *Chapter 3* shows the results of the literature review: a description of all found models, a comparative analysis of the most interesting tools for rural modelling and a final discussion.

1 Sustainable Energy for all and the role of Energy modelling

1.1 The importance of Sustainable Energy for all

Energy is very important from a sustainable point of view, especially for socio-economic development, quality of life for the people, global security and environmental protection. In fact, it allows to satisfy the most basic human needs: cooking, light, space heating, water heating and water extraction. Furthermore, energy is the basis for most economic activities: food production, transport, commercialization, agriculture, or simply the production of commodities to elaborate other products or supply services. Energy is also essential for protecting human health (**Figure 1.1**) and environment: access to electricity and to clean cooking facilities can help to avoid premature deaths, diseases, local air and water pollution, indoor pollution, deforestation, ecosystem damages, CO2 emissions, etc. Additionally, wood collection is highly time-consuming, especially for women and children because this limits their time available for education and expose them to frequent phenomena violence.

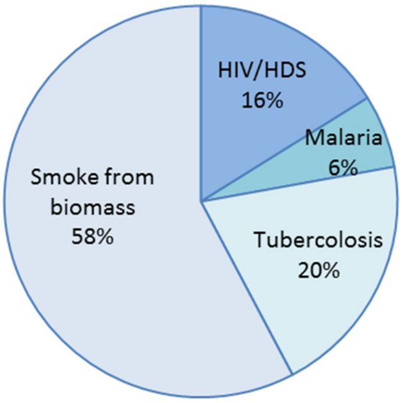


Figure 1.1 Deaths per year on a global scale. Data from: IEA.

Additionally, it is stated that there is a link between access to energy and income, access to energy and quality of life, access to energy and development. This is shown by the graph in the **Figure 1.2**, in which the electricity consumption per person per year is compared to an index representing not only the economic growth of a country, but also other dimensions of development: the Human Development Index (HDI). More specifically, it is the geometric mean between [3]:

- Life Expectancy Index (LEI) that takes into account the life expectancy at birth;
- Education Index (EI) which is assessed by mean of years of schooling for adults aged 25 years and more and expected years of schooling for children of school entering age;
- Income Index (II) measured using the logarithm of Gross National Index per capita.

In this way it is possible to consider economic, educational, health aspects and so the quality of life level all together. The graph shows the dependence of the consumption, and therefore the access to electricity, from all these dimensions: the developed countries (in blue) are characterized by high HDI and high kWh/yr per person, while the developing countries (red for Africa, Green for Asia, Violet for Latin America) are identified by relatively low HDI and low value of electricity consumption per year per person. Sometimes the HDI is distorted and increased by the fact that in a country could be a part of population which lives in very good life conditions and other part that is poor and lives in rural areas: the inequalities in such countries are very high and are not take into account by HDI that, consequently, could be higher than the real one.

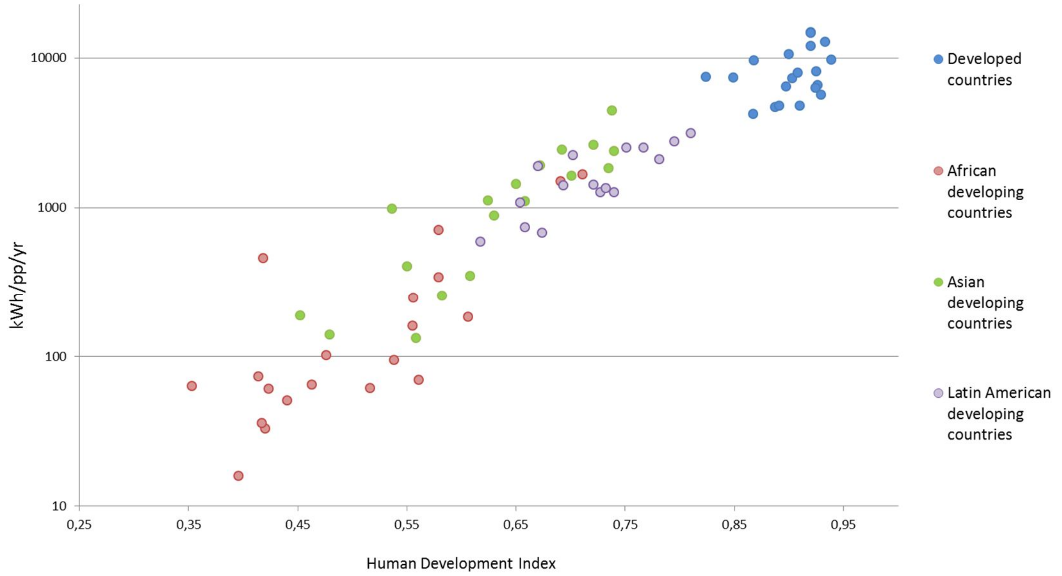


Figure 1.2 Relation between HDI and electricity consumption of some countries in the world. Data from: UNDP and IEA.

In this regard, the United Nations set 17 Sustainable Development Goals (SDGs), which replace the previous Millennium Development Goals and cover a broad range of sustainable development issues. Specifically, Goal 7 (Affordable and Clean Energy) states "Ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030 [3]. The challenges include security, affordability and resilience of energy supply, as well as environmental concerns.

However, projections by the International Energy Agency (IEA) indicate that, despite reducing the fraction of those without access to electricity by 20%, close to 1 billion people will remain without access in 2030. Similarly, projections also indicate that around 2.6 billion people, a little more than 30% of the global population, will still remain without access to modern cooking fuels in 2030 [4] (**Figure 1.3**).

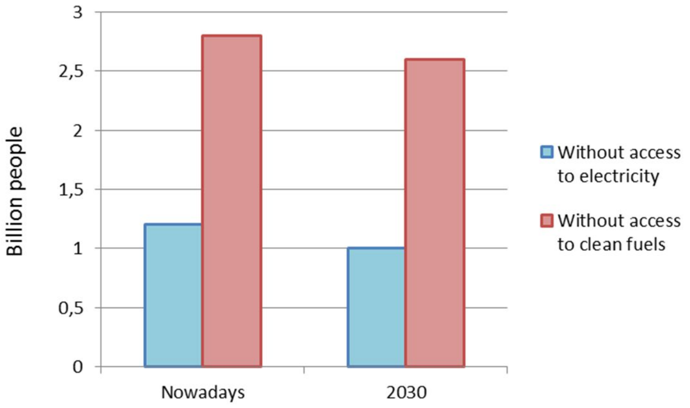


Figure 1.3 Number of people without access to energy in the world: nowadays VS 2030. Data from: IEA.

1.2 The Need for New Energy System Models

Energy models were first developed in the 1970s as a result of the increasing availability of the computer and as a consequence of the oil crisis, when both industry and policymakers realized the importance of long-term strategic energy planning and of energy stability. Most of the energy models were built and used in industrialized countries. Among them, MARKAL (the MARKet ALlocation model) and MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental impact model) were the first to be developed and used [5].

The energy systems of industrialized countries are characterized by a constant match of supply and demand, low losses of transmission and distribution, universal access to electricity, predominance of modern energy carriers, similar structural premises in urban and rural areas, adequate financing and investment decisions, adequate subsidies and profit-making utility companies in developed economies with a low extent of informal economies[6]. To the contrary, the energy systems of developing countries differ from those of industrialized countries and among each other. As a consequence, the tools built for modelling energy systems in industrialized countries are inappropriate for small energy systems planning in developing countries: since the two type of systems are characterized by different features, they need also different modelling tools, otherwise the results could be wrong and inefficient.

The energy system in developing countries are mainly characterized by the following features:

- the demand is not constant, due to the fact that population is continuously growing;
- no security of energy supply: sometimes, the available energy systems does not met the demand. This leads to frequent plant breakdown, outages and voltage fluctuations, resulting in unreliable service causing economic losses. This situation could be caused by:
  - a poor performance of the power sector (poor conditions of generation and distribution equipment, inadequate operational and maintenance performance and a high level of technical and non- technical losses),
  - a rapidly growing demand for electricity,
  - a low number of power plants,
  - technical constraints,
  - a dependence on import of plants and equipment for power supply,
  - fluctuations of renewable energy sources;
- unpaid bills;
- high transmission and distribution losses (mainly due to theft of electricity);
- predominant fuels are traditional bio-fuels (in this case, the problem is that the stocks are decreasing while the population is increasing and there is an unavailability of alternative fuels);
- low or null access to electricity because these rural areas are far from the grid (no possibility to connect to existing grid because of the presence of some natural obstacles or due to the fact that the high costs do not allow it. In cases in which the extension could be feasible,

maybe the cost of transmission and the losses may be too high because of the topography of the ground);

- under-financed power companies;
- restriction on capital available for adequate investments;
- no adequate subsidies.

Moreover, mankind has to realize that the issues concerning the developing countries affects not only the local pollution and the local energy resources stocks, but also the global climate change and the world's energy reserves. Therefore, energy system situation of the developing countries is a complex and serious challenge that affects and concerns all mankind.

To address the problem of rural electrification, different strategies can be employed [3]:

- Extend the national existing grid to sparsely populated area: cost of energy delivered would be low but investment costs as well as technical losses due to long distances could be very high.
- Off-grid systems: distributed generation could be an effective solution in remote areas because it allows to exploit local energy resource and to reduce energy dependency by coupling small-scale fossil-based and renewable-based energy technologies. Furthermore, it is suitable for a small scale electricity production, usually typical of such isolated areas, even though it requires high investment cost. Off-grid systems can range from home based systems relying on a single source and consumer to micro-grids integrating more than one source of energy and than one consumer.
- Integrated micro-grids: they can be defined as an aggregation of micro-grids operating as single system providing both power and heat, integrated to national grid or not. They have their internal control and optimization scheme and could operate in connection with the main grid. This could be useful to reduce the discontinuity of supply and the dependence on batteries, that are the most problematic components for the cost but also for the dismantling.

Therefore, although a centralized approach would be more cost-effective in a long term perspective, it can be stated that decentralized systems represent the most effective solution for the near future in these isolated areas.

2 Methodology

There exists a large number of different models and software tools for the optimization, design, analysis and economic planning of energy systems. They can differ for example for the regions they analyse, the technologies they consider, the objectives they fulfil, the type of analysis they perform. Therefore, a comprehensive literature review, to support the identification of the most suitable tool for specific purposes and needs, is necessary.

This work wants to focus the attention on models best suited to ensuring a correct energy system modelling in rural areas. This means that the main characteristics of the model, as already anticipated in the introduction, must be:

- small scale of the energy system considered;
- bottom up approach: in this way model is independent of market behaviour and production frontiers and technologies are explicitly modelled;
- micro-grids and stand-alone application possibility: most of the times these rural areas are far from the existing network. Therefore, the extension of the grid could be too expensive and complex;
- presence of renewable energy technologies, storage systems and conventional fuels: to exploit local resources and to avoid shortages;
- short scenario timeframe: in these areas everything is constantly changing (an example could be the trend of the demand);
- temporal and spatial resolution has to be able to take into account the continuous variations occurring in these areas and the intermittency of renewable energy sources.

2.1 Classification criteria of tools

The starting point of the literature review is to type specific key words and sentences on search engines and databases such as Scopus, Google Scholar, Science direct. Some examples are: *computer tools for energy systems*, *software tools for energy systems*, *energy models*, *energy system models*, *review of energy tools*, *review of energy models*, *open energy models*, *electrification models*, etc. Moreover, other information is found on the web by typing the name of the tool followed by *energy tool*, *energy model*, *energy framework*, *energy software* or by the name of the main developer or author. In this way it is possible to find papers, thesis, reference websites, documentation, user manuals, training guides, presentations, papers and other material about each specific model.

Only some among the found tools are considered the most suitable and the most complete ones to ensure correct energy system modelling in rural areas. From now on, they will be called *strong tools* and they will be described in detail in the section 3.1.3. Other tools are not considered at all because they are not suited for the purpose of this work. In fact, they cover a too large scale or they are not appropriate for multi-energy system modelling. For this reason only a brief and rough description of them will be performed in section 3.1.1. They will be called *out of scope tools*. Among the remaining tools, some could be appropriate for the purpose of the work, but they will be described only in a very general way because there are not enough material or information about or because they are no longer used or modified since long time, others could be suitable for small scale energy systems modelling but they do not satisfy all the necessary conditions for energy system design in rural areas. From now on, they will be called *weak tools* and only a brief description and general information about the main developer, the main purpose, the actual availability, the main characteristics will be reported in section 3.1.2.

2.2 Evaluation criteria of “strong tools”

The descriptive analysis carried out in section 3.1 is helpful in section 3.2 to perform a comparative analysis of the so called *strong tools*. More specifically, it highlights:

- the availability and the openness of each tool;
- the geographical scale covered;
- the type of analysis performed;
- the technologies and the energy sectors considered;
- the mathematical approach adopted
- the spatial detail;
- the user-friendliness and the flexibility;
- how many times a tool is cited in scientific literature.

At the end, in section 3.3, a SWOT analysis is shown, in order to highlight drawbacks and benefits of each *strong tool* and to provide a support in the decision of the most proper tool for a specific purpose.

In particular, for the section related to the citations in literature, another online research is carried out. Once again, the instrument used is Google Scholar. During the analysis, the name of each tool followed by *model*, *software*, *framework* or by the name of the main developer is typed on the so called *advanced search* section of this research engine. All papers, thesis, books, preprints, abstracts, reviews, reports in which these words appear, are taken into account.

Specifically, the words used are:

- *HOMER model* and *HOMER software*
- *DER-CAM model* and *DER-CAM software*
- *Local Reference Electrification Model*
- *Micro-Grids Sergio Balderrama*
- *Multi Energy System*
- *Calliope framework*

- *poli.NRG software*
- *open energy modelling framework*
- *OSeMOSYS model* and *OSeMOSYS software*
- *URBS tum-ens*
- *ficus Dennis Atabay*
- *iHOGA software*
- *INSEL model* and *INSEL software*
- *H2RES model* and *H2RES software*
- *TOP-Energy framework* and *TOP-Energy software*

When there is more than one option, the numbers of found citations are added together, paying attention to the papers that appear more than one time. Obviously, they are considered only once.

3 Results of Literature Review

The review gives a lot of interesting papers about appropriate tools to model energy systems [1], [7], [16]–[22], [8]–[15] . Nevertheless, at the very beginning, only two of these are considered because they seem to be the most thorough.

The first paper [7] is by Connolly et al. and it is entitled "A review of computer tools for analysing the integration of renewable energy into various energy systems", 2010. The results provide the information necessary to identify a suitable energy tool for analysing the integration of renewable energy into various energy-systems under different objectives. From the 37 tools reviewed in the paper, only HOMER (local, community), H2RES (island), RETScreen (user-defined), TRNSYS (local, community), COMPOSE (single-project investigation), HYDROGEMS (single-project investigation), energyPRO (single-project investigation) seem to be suitable for small scale energy systems; the other ones (AEOLIUS, BALMOREL, BCHP Screening Tool, E4cast, EMCAS, EMINENT, EMPS, EnergyPLAN, ENPEP-BALANCE, GTMax, IKARUS, INFORSE, Invert, LEAP, MARKAL/TIMES, Mesap PlaNet, MESSAGE, MiniCAM, NEMS, ORCED, PERSEUS, PRIMES, ProdRisk, RAMSES, SimREN, SIVAEL, STREAM, UniSyD, WASP, WILMAR Planning Tool) consider energy systems for too large geographical area and for purposes different from the main one.

The second paper [8] is by Sinha et al. and it is entitled "Review of software tools for hybrid renewable energy systems", 2014. The main objective of the paper is to provide the current status of some softwares to give basic insight to identify and utilize suitable tool for research and development studies of hybrid systems. The capabilities of different softwares are also highlighted. The limitations, availability and areas of further research have also been identified. All of the 19 softwares (HOMER, iHOGA, INSEL, HYBRID2, iGRHYSO, HYBRIDS, RAPSIM, RETScreen, SOMES, SOLSTOR, HySim, HybSim, IPSYS, HySys, Dymola/Modelica, ARES, TRNSYS, SOLSIM, Hybrid Designer) presented in the paper seem to be interesting for the purpose of the work.

Other suitable tools (DER-CAM, LREM, oemof, OSeMOSYS, Calliope, URBS, ficus, poli.NRG, TOP-Energy, Micro-Grids py, Multi energy system py, HYPORA, RESCOM, DESDOP) are found in the following websites: [23]–[25].

Table 3.1 The tools groups.

Total tools	*Strong tools*	*Weak tools*	*Out of scope tools*
67	15	22	30

Among these 67 selected tools, only 15 (HOMER, H2RES, INSEL, iHOGA, DER-CAM, LREM, oemof, OSeMOSYS, Calliope, URBS, ficus, poli.NRG, TOP-Energy, Micro-Grids py, Multi energy system py) are considered the most suitable to ensure a correct energy system modelling in rural areas. They are the so called *strong tools*. Other 22 tools, called *weak tools,* (HYBRID2, iGRHYSO, HYBRIDS, RAPSIM, RETScreen, SOMES, SOLSTOR, HySim, HybSim, IPSYS, HySys, Dymola/Modelica, ARES, TRNSYS, SOLSIM, Hybrid Designer, HYPORA, RESCOM, DESDOP, COMPOSE, energyPRO, HYDROGEMS) could be appropriate for the purpose of the work but there are not enough material or information about or they are no longer used or modified since long time or they are more useful for goals other than the multi-energy system modelling in rural areas. The last 30 tools (AEOLIUS, BALMOREL, BCHP screening Tool, E4cast, EMCAS, EMINENT, EMPS, EnergyPLAN, ENPEP-BALANCE, GTMax, IKARUS, INFORSE, Invert, LEAP, MARKAL/TIMES, Mesap PlaNet, MESSAGE, MiniCAM, NEMS, ORCED, PERSEUS, PRIMES, ProdRisk, RAMSES, SimREN, SIVAEL, STREAM, UniSyD, WASP, WILMAR Planning Tool) are *out of scope* at all because they are not suited at all for the purpose of this work. (**Table 3.1**).

3.1 Description of tools

3.1.1 Out of scope tools

In **Table 3.2** it is possible to find some basic information about the tools not considered in this work, the so called *out of scope tools*. Such information are collected mainly from Connolly paper [7] and from the following website [26].

Table 3.2 *Out of scope tools* basic features. Adapted from Connolly paper [7].

TOOL	Organization	General Characteristics	Geographical Area	Scenario Timeframe
AEOLIUS	Institute for Industrial Production, Universität Karlsruhe	Power-plant dispatch simulation tool	National/state/regional	1 year
BALMOREL	Project Driven with a users network and forum around it	Partial-equilibrium tool with an emphasis on the electricity sector and CHP	International	Max 50 years
BCHP Screening Tool	Oak Ridge National Laboratory	Computer program for assessing the savings potential of combined cooling, heating and power systems for buildings	Single-project investigation	1 year
E4cast	Australian Bureau of Agricultural and Resource Economics	Partial-equilibrium tool for Australian energy-system	National/state/regional	Max 50 years
EMCAS	Argonne National Laboratory	Power system operation simulation tool for electricity market	National/state/regional	No limit
EMINENT	Instituto Superior Técnico, Technical University of Lisbon	Tool designed to help introduce new energy technologies and new energy solutions into the market in a faster way	National/state/regional	1 year
EMPS	Stiftelsen for Industriell og Teknisk Forskning (SINTEF)	Computer tool for the simulation and optimization of the operation of power systems with a certain share of hydro power	International	25 years

EnergyPLAN	Aalborg University	User-friendly tool to assist in the design of the energy planning strategies by simulating the entire energy-system	National/state/regional	1 year
ENPEP-BALANCE	Argonne National Laboratory	Non-linear, equilibrium tool to match the demand for energy with available resources and technologies	National/state/regional	75 years
GTMax	Argonne National Laboratory	Simulation tool for the dispatch of electric generating units and the economic trade of energy among utility companies	National/state/regional	No limit
IKARUS	Research Centre Jülich, Institute of Energy Research	Dynamic bottom-up linear cost-optimization scenario tool	National/state/regional	Max 50 years
INFORSE	The International Network for Sustainable Energy	Energy balancing tool	National/state/regional	50+ years
Invert	Energy Economics Group, Vienna University of Technology	Simulation tool for the design of efficient promotion schemes for renewable and efficient energy technologies	National/state/regional	Max 50 years
LEAP	Stockholm Environment Institute	Integrated modelling tool used to track energy consumption, production and resource extraction in all sectors of an economy	National/state/regional	No limit
MARKAL/ TIMES	Energy Technology Systems Analysis Program, International Energy Agency	Energy/ economic/ environmental tools	National/state/regional	Max 50 years
Mesap PlanNet	seven2one	Energy-system analysis toolbox (Mesap) and linear network module (PlaNet) for the analysis and simulation of energy supply, demand, costs and environmental impacts	National/state/regional	No limit
MESSAGE	International Institute for Applied Systems Analysis	Optimization tool used for the planning of energy systems, analyzing climate change policies and developing scenarios	Global	50+ years
MiniCAM	Pacific Northwest National Laboratory	Fast and flexible partial-equilibrium tool to examine changes in energy and agriculture systems	Global and regional	50+ years
NEMS	Office of Integrated Analysis and Forecasting, Energy Information Administration	Energy–economy–environmental tool for the US energy-markets	National/state/regional	Max 50 years
ORCED	Oak Ridge National Laboratory	Electricity dispatch simulation tool	National/state/regional	1 year

PERSEUS	Institute for Industrial Production, Universität Karlsruhe	Energy and material flow tool	International	Max 50 years
PRIMES	National Technical University of Athens	Market equilibrium simulation tool for energy supply and demand	National/state/regional	Max 50 years
ProdRisk	Stiftelsen for Industriell og Teknisk Forskning (SINTEF)	Optimization and simulation of hydro-thermal systems	National/state/regional	Multiple years
RAMSES	Danish Energy Agency	Simulation tool of electricity and heat district production primarily used in the Nordic market	International	30 years
SimREN	Institute of Sustainable Solutions and Innovations	Software for the design of ‘close to reality’ models of energy supply and demand systems	National/state/regional	No limit
SIVAEL	Energinet.dk	Simulation program for electricity sector and district-heating systems	National/state/regional	1 year
STREAM	Ea Energy Analyses	Scenario building tool for decision-making in national energy systems	National/state/regional	1 year
UniSyD3.0	Unitec New Zealand	Multi-regional partial-equilibrium tool for energy and economic systems	National/state/regional	Max 50 years
WASP	International Atomic Energy Agency	Tool for finding an optimal expansion plan of a power generating system	National/state/regional	Max 50 years
WILMAR PlanningTool	Risø DTU National Laboratory for Sustainable Energy	Optimal operation of power systems with wind integration	International	1 year

How it is possible to notice from the table, these tools are characterized by geographical coverage too large, by a scenario timeframe that is too long and by general characteristics that are far from the design of a rural multi-energy system.

3.1.2 Weak tools

In order to describe each minor tool, information about them is taken from the references of papers that mention them. In **Table 3.3**, the main papers talking about *weak tools* are shown.

Table 3.3 List of references referred to *weak tools*.

References	COMPOSE	RETScreen	TRNSYS	HYBRID2	SOMES	HybSim	IPSYS	RAPSIM	RESCOM	DESDOP	SOLSIM	SOLSTOR	HySim	HYSYS	Hybrid Designer	Dymola/ Modelica	HYDROGEMS	energyPRO	ARES	iGRHYSO	HYBRIDS	HYPORA
[1]		x																				
[7]	x	x	x														x	x				
[8]		x	x	x	x	x	x	x			x	x	x	x	x	x				x	x	
[9]				x															x			
[10]		x		x	x	x	x	x				x	x	x		x						
[11]				x																	x	
[12]		x	x	x													x					
[13]		x	x	x	x			x			x				x							
[14]		x		x	x			x			x											
[15]																						
[16]			x	x		x		x			x						x		x		x	
[17]			x																			
[18]		x	x	x	x			x			x				x							
[19]				x	x																	
[20]		x																				
[21]				x	x			x			x				x							
[22]									x	x												

3.1.2.1 COMPOSE

COMPOSE stands for "Comparing Options for Sustainable Energy" and is a techno-economic energy project assessment tool developed by Aalborg University in Denmark in 2008. It can be freely downloaded from [27]. The tool is also a social platform that enables the users to share and compare their projects [28]. The aim of COMPOSE is to assess to which degree energy projects may support intermittency, while offering a realistic evaluation of the distribution of costs and benefits under uncertainty [7]. Furthermore, it evaluates a project regarding economic, financial and fiscal costs, CO2 emissions and consumption of primary energy resources [28]. COMPOSE identifies the option's operational strategy by mixed-integer linear programming under the objective function of minimizing the economic cost of meeting the demand for the period of the simulation under given techno-economic constraints and boundaries. The tool has a user-defined system which means that it can simulate all financial aspects as well as all thermal generation, renewable energy, storage/conversion and transport technologies in a single-project investigation. However, it does focus particularly on cogeneration with an electric boiler or compression heat pump. The analysis is carried out using a one-hour time-step over a user-defined number of years [7].

In 2008 COMPOSE has been used in [29] to help identify options for dealing with intermittency, related to large scale penetration of wind power on the West Danish energy-system, and in [30] to analyse the benefits of energy storage and relocation options. It has also been used in [31] in order to perform an optimization for a sustainable energy system for a 100% renewables based Smart House; the analysis involves detailed technical specifications and considerations for providing optimal supply of electricity, heating, cooling, and hot tap water demand, balancing fluctuating wind power and both solar power and solar thermal supply utilizing advanced heat pump and both electro-chemical electricity storage, and hot and cold thermal storages.

3.1.2.2 RETScreen

RETScreen is a technical and financial feasibility study tool developed by Ministry of Natural Resources, Canada in 1998. It is freely downloadable from [32]. Online it is also possible to find user manuals, tutorials, textbooks and flyers [33], [34] [35][36].

It can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of ‘Renewable-energy and Energy-efficient Technologies’ (RETs). Fundamental to RETScreen is a comparison between a ‘base case’, typically the conventional technology, and a ‘proposed case’ which is typically the clean energy technology. The comparison includes all costs and a number of economic indices i.e. internal rate of return (IRR) and net present value (NPV). The software can be applied to any energy-system, ranging from individual projects to global applications. All thermal generation and renewable technologies can be accounted for using RETScreen and it can incorporate energy efficiency measures relatively easily. However, the only storage/conversion device considered is battery energy storage, and it cannot model any transport technologies [7]. First released for on-grid applications, the RETScreen PV model was than upgraded to also cover off-grid PV applications. These include stand-alone, hybrid and water pumping systems. RETScreen has a global climate data database of more than 6000 ground stations (month wise solar irradiation and temperature data for the year), energy resource maps (i.e. wind maps), hydrology data, product data like solar photovoltaic panel details and wind turbine power curves. It also provides link to NASA climate database [8].

RETScreen model has been used in [37] for assessing potential PV projects, in [38] to check environmental, technical and financial feasibility of solar power plants according to the targeting of energy subsidies in Iran, in [39] to perform a feasibility analysis of a wind-PV-battery system for an off-grid power station specially located in remote village of Dongwangsha, Shanghai. It has been also used to assess the feasibility of wind farm development in Algeria [40], the feasibility of solar water heating in Lebanon [41], the viability of solar PV in Egypt [42], as well as identifying GHG reductions in the residential sector [43].

3.1.2.3 TRNSYS

TRNSYS is a commercial [44], [45] transient systems simulation program, developed in 1975 by the University of Wisconsin and University of Colorado. It does not provide optimization facilities but it carries out simulation with great precision with graphics and other details [8]. TRNSYS has an open modular structure with open source code which simulates the electricity and heat sectors of an energy-system. It simulates the performance of the entire energy-system by breaking it down into individual components, and it is primarily used for analysing single-project, local community, or island energy-systems. It can simulate all thermal and renewable generation except nuclear, wave, tidal, and hydro power. The only electrical energy storage considered by TRNSYS is battery energy storage, while hydrogen systems are simulated in detail using the formally independent tool, HYDROGEMS (see …). The tool uses a user-defined time-step, which ranges from 0.01 seconds to 1 hour and it can analyse a time-horizon of multiple years [7].

TRNSYS has been use in [46] to perform a feasibility study of a trigeneration plant intended to integrate the existing natural gas fired-boiler central plant serving a 714 bed hospital located in Parma, North of Italy, in [47] for model and simulate a hybrid PV–thermal solar system in Cyprus and in [48] to analyse and to investigate two different principles of thermoelectric cogeneration solar collectors. TRNSYS has also been used to model an ICS solar water heater [49], to perform an optimal design of a forced circulation solar water heating system for a residential unit in cold climate [50] and to check the effect of fixed horizontal louver shading devices on thermal performance of building [51]. TRNSYS training manuals, user guides, fliers are also available online [52]–[55].

3.1.2.4 HYBRID2

HYBRID2 was developed in 1994 by Renewable Energy Research Laboratory (RERL) of the University of Massachusetts, USA with support from National Renewable Energy Laboratory. Although it can be freely downloaded and installed with a password, it is no longer supported. In fact, the major downfall of this tool is that it may be out-dated.

It is a simulation tool that aims to provide detailed long term performance and techno-economic analysis on a wide variety of hybrid power systems [21]. It also incorporates probabilistic analysis to account for variation in resources and demand.

HYBRID 2 has a provision of time series simulations for time steps typically between 10 min and 1 h. it allows systems based on three buses containing wind turbines, PV array, diesel, battery storage, power converters and a dump load. Nevertheless, the code does not consider short term system fluctuations caused by system dynamics or component transients [8].

HYBRID 2 mainly contains four blocks namely the Graphical User Interface (GUI), the Simulation Module, the Economics Module and the Graphical Results Interface (GRI). The GUI allows to construct projects easily and maintain an organized structure to all of the current projects; The Simulation and Economics Modules allow the user to run simulations with relative ease and includes error checking of inputs; The GRI allows the user to easily view the detailed output data in a graphical form without leaving the Hybrid2 environment [56]–[58]. This software tool has a limited access to parameters and lack of flexibility but it has a library with various resource data files.

HYBRID2 has been used to simulate the operation of a photovoltaic hybrid system installed in Genec's testing facilities [59] to design and analyse an hydrogen-based hybrid system using the renewable resources available in Chicago [60] and a hybrid (PV/wind/diesel) power system [61].

3.1.2.5 SOMES

SOMES (Simulation and Optimization Model for renewable energy systems) has been developed at Utrecht University (The Netherlands) in 1987 and it is available for a nominal fee. It simulates and analyses the operation of hybrid systems consisting of PV arrays, wind turbine and diesel generator or grid connection for generating electricity and batteries for storage. The system performance is evaluated technically and financially. The time step of the simulation is one hour and the objective function of the optimization is the minimization of the electricity cost [21]. Nowadays it is very difficult to find papers and publications about SOMES because is out-dated and it is no longer used.

3.1.2.6 HybSim

HybSim (short for Hybrid simulator) was developed by Sandia National Laboratories, USA. It is a tool design to evaluate the economic and environmental benefits of adding renewable energy to fossil fuel generation mix in remote and difficult-accessible locations. The components allowed are PV panels, batteries and generators [62].

In 2003, the HybSim model was used to model the performance of the electrical generation system in Lime Village, Alaska [63]. HybSim was used also to quantify the benefits of operating diesel-battery hybrid generating as compared to diesel-only systems in remote villages.

HybSim version 1 (2005) is available for license and is undergoing development. Despite this the tool is no so used and documentation or other information material about it is few and out-dated.

3.1.2.7 IPSYS

IPSYS (Integrated Power SYStem) is a hybrid simulation modelling tool for technical performance analysis of isolated and interconnected energy systems [64]. No Graphical User Interface option is available but some scripts can be used to analyse graphical output. IPSYS is composed by a component library and it is able to make simulation of electricity generation through PV arrays, wind turbines, diesel generators, energy storage batteries, hydro reservoirs, fuel cells as well as natural gas [8]. The way to download the model is unknown and there is no a lot of material to collect information about it. Maybe this is the reason why IPSYS is not so known and developed.

From [65] it is possible to understand that IPSYS has been used for different case studies: a diesel/hydro/wind system in Faeroe Islands and a refrigerated warehouses for large-scale demand response. IPSYS has been also used to evaluate smart grid control strategies in co-simulation [66].

3.1.2.8 RAPSIM

RAPSIM (Remote Area Power SIMulator) was developed by Murdoch University Energy Research Institute (MUERI), Australia in 1996. It is a Windows based software package for hybrid system model. This program simulates systems comprising of PV arrays, wind turbines and diesel generators with batteries. In 1997 version 2 of this software was available but whether updates after that year have been made to the software or not, is not clear [8] [67].

3.1.2.9 SOLSIM

SOLSIM, developed at Fachhochschule Konstanz, Germany, is a simulation program. It enables the user to design, analyse and optimize off grid, grid connected and hybrid solar energy systems using PV panels, wind turbines, diesel generators, batteries and bio-energy systems for electricity and heat generation. A graphic user interface including topic related help functions makes the program easy to learn and to use [68]. This software is no longer available.

3.1.2.10 SOLSTOR

Sandia National Laboratory (SNL) developed a model in late 1970s and early 1980s known as SOLSTOR. It carries out economics and optimization analysis for various Hybrid systems including renewable energy components like PV arrays, wind turbines etc., storage batteries and other power conditioning options and utility grid or fuel burning generator can be also used as backup electricity provider. The model can be run with on grid and off grid condition both [8]. SOLSTOR minimizes the life cycle cost of providing energy by choosing optima components size. But now this model is no longer used and updated.

3.1.2.11 HySim

Hysim is a hybrid energy simulation model developed by Sandia National Laboratories, US in 1986. It is used to evaluate stand-alone off-grid hybrid systems consisting in PV panels, diesel generators and battery storage combination. The aims of this model is to evaluate the increasing of the overall system reliability by adding PV and battery storage. Hysim carries out also financial analysis including Life Cycle, fuel, Levelized Cost of Energy, and operation and maintenance costs, and cost comparisons between different configurations. Hysim has not been used after 1996 [8].

3.1.2.12 HYSYS

Hysys, or Hybrid Power System Balance Analyzer, was developed at the Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT) institute in Spain by their wind technology group. It is a hybrid simulation tool for sizing and long-term analysis of off-grid systems mainly comprising of PV arrays, wind turbines and diesel generators for the production of electricity. In 2003 version 1.0 of this software was developed but now it is currently being used internally by CIEMAT only [8].

3.1.2.13 Hybrid Designer

Hybrid Designer was developed at the Energy and Development Research Center (EDCR) of Cape Town in South Africa and was funded by the South African Department of Minerals & Energy. It is a tool that should help to design off grid applications in Africa’s rural areas. It is user friendly software based on genetic algorithm which can evaluate different configurations with minimum lifecycle cost. The genetic algorithm copies the idea of evolution by excluding bad solutions and generating better ones based on the good solutions. A simulation based on a given scenario is finished when a terminating condition is met (e.g. no further reduction in costs). Hybrid Designer can simulate different sources such as photovoltaics, wind generator, battery and an engine generator [8] [68].

3.1.2.14 Dymola/ Modelica

Dymola/Modelica is a programming language used by the Fraunhofer Institute for Solar Energy (ISE) in Germany for modelling hybrid systems composed by PV, wind turbines, generators, fuel cells and battery storage. It can evaluate lifecycle costs and calculate levelized cost of energy but now update status of this software is unknown [8].

3.1.2.15 ARES

ARES (Autonomous Renewable Energy system) is a program developed at the Cardiff school of engineering, University of Wales, UK for simulation of PV–wind–battery systems. This software can calculate the system loss of load probability and system autonomy by the prediction of the storage battery voltage if input load and essential weather profile are provided. The software has two versions ARES-I and modified version of ARES-I by Morgan et al. [28] is known as ARES-II. ARES-I consisted of subroutine program in the following order: weather statistics, photovoltaic generation, wind generation, load calculation, combined source and load current, battery voltage subroutine, controller action, and presentation of results. ARES-II required load and basic weather profile inputs and calculates the system loss of load probability and system autonomy using storage battery voltage prediction. Despite this, the software is no longer available now [8][69].

3.1.2.16 iGRHYSO

iGRHYSO (improved Grid-connected Renewable HYbrid Systems Optimization) is the improved version of the GRHYSO and it was developed by the University of Zaragoza, Spain. It is available only in Spanish language. iGRHYSO is a software for grid connected hybrid renewable energy systems simulation and optimization. It considers various renewable energy system like photovoltaic, wind, small hydro, etc. with storage batteries using different technologies or hydrogen. The connection of this software with the NASA website is helpful for importing irradiation, wind and temperature data. The tool can also study the effects of temperature on photovoltaic generation and production by wind turbines and calculate the Internal Rate of Return (IRR). This software can export simulation data in excel spreadsheet format. The problem with iGRHYSO is that the current status is unknown [8] [70].

3.1.2.17 HYBRIDS

HYBRIDS is produced by Solaris Homes. It is commercially available but it is unknown the way to download it. HYBRIDS is a Microsoft Excel spreadsheet-based and renewable energy system assessment application and design tool. It can only simulate one configuration at a time, and is not designed to provide an optimized configuration. It is particularly used to improve design skills about renewable energy systems [8].

3.1.2.18 HYPORA

Pennsylvania State University, USA tries to create an optimization tool that considers wind, solar and biomass resources to determine how these three sources of energy would be best combined into a hybrid small scale system to meet the electricity demand. The tool, named HYPORA (Hybrid Power Optimized for Rural/Remote Areas), takes into account not only the scientific basis of renewable energy, but also economic and need factors, including government incentives. It is based on Microsoft EXCEL platform and can be used by engineers and scientists, as well as general public, policymakers, investors and students, due to its user-friendliness. HYPORA can be used to see how different levels of investment could build systems to meet power requirements for rural/remote areas, and determine the levelized cost of energy in a specific region. Also it can be used to determine power production as well as to examine the effects of feed-in tariffs and government subsidies. HYPORA utilizes some simplifications: since it uses averages for the year it can only provide the average daily output. The production may vary greatly by season and the weather may not be consistent from year to year, resulting in numbers that may be different from the average values. As a consequence also the values for wind speed and solar irradiation may fluctuate from year to year, as may the price of components, operation and maintenance, etc. nowadays HYPORA is still under development [71] [72].

3.1.2.19 RESCOM

RESCOM (Residential Energy System Conceptual Optimization Model) models the energy required for supplying space heating and domestic hot water services to aggregated groups of existing residential buildings. It considers both supply-side (energy conversion equipment) and demand-side (building insulation) optimization. Moreover, the tool reflects the spatial arrangement of the conversion units in the modelled area. It has been formulated as a MILP (mixed-integer linear programming) to both deal with integer variables and to allow for large scale modelling efforts. The boundary conditions of RESCOM can handle both the existing heating demand of residential buildings, and the heating equipment and networks required to meet this demand. The objective function of the model represents minimization of costs, discounted to today’s value [22] [73]. RESCOM has been developed at the Imperial College, UK.

3.1.2.20 DESDOP

DESDOP (District Energy System Design and OPtimization model) has the purpose to define the mix of technologies that will best meet the energy service requirements of a small city. The technologies considered include both renewable and non-renewable powered technologies, as well as centralized and distributed technologies. The objective function, defining the optimal mix of technologies, can be expressed in terms of costs or emissions. The resulting mix of technologies, together with the (potential) distribution network, represents the district energy system of the analysed small city. Any combination of technologies is possible: from totally centralized to totally distributed; from 100% of the energy services met with renewable energy to 100% met by non-renewable energy. The tool integrates an evolutionary algorithm with and deterministic MILP optimization. It is implemented in GAMS algebraic modelling using the Cplex Mixed Integer Linear Programming optimizer [22] [74]. DESDOP has been developed at the Imperial College, UK.

3.1.2.21 HYDROGEMS

HYDROGEMS is a set of hydrogen energy tools suitable for the simulation of integrated hydrogen energy-systems, particularly renewable energy based stand-alone power systems. The tools have been developed at the Institute for Energy Technology since 1995 first as part of a PhD-study and later in various projects. In 2006 HYDROGEMS was fully integrated into TRNSYS16. It is commercially available but free for TRNSYS users. The tools are particularly designed to simulate hydrogen mass flows, electrical consumption and electrical production, but they can also be used to simulate the thermal performance of integrated hydrogen systems. The component tools available in HYDROGEMS-library are wind energy conversion systems, photovoltaic systems, water electrolysis, fuel cells, hydrogen gas storage, metal hydride hydrogen storage, hydrogen compressor, secondary batteries (lead-acid), power conditioning equipment and diesel engine generators (multi-fuels, including hydrogen). From a financial viewpoint, fuel prices, investment, fixed O&M and variable O&M costs can all be accounted for [7].

HYDROGEMS was initially used to analyse the operation of a stand-alone PV-hydrogen system [75]–[78], but more recently is has been used to investigate stand-alone wind-hydrogen systems [79]–[81].

3.1.2.22 energyPRO

energyPRO is a commercial tool, developed and maintained by the company EMD International A/S in Denmark. It is a complete modelling software package for combined techno-economic design, analysis and optimization of both fossil and bio-fuelled cogeneration and trigeneration projects, as well as wind power and other types of complex energy-projects. Nevertheless, it is specifically designed for a single thermal or CHP power-plant investigation. It can model all types of thermal generation except nuclear, all renewable generation and all energy storage units to complete the analysis. The analysis is carried out using a one-minute time-step for a maximum duration of 40 years. In addition, energyPRO accounts for all system costs along with SO and NO penalties [7].

energyPRO has been used to analyse CHP plants participating in the spot market or selling electricity at fixed tariffs [82], to simulate compressed-air energy storage in the spot market [83], to analyse CHP plants instead of boilers on district-heating networks [84] and to identify the optimal size of a CHP unit and thermal storage when a CHP plant is selling on the spot market [85]. Moreover, energyPRO has modelled single-projects where 100% of the demand was supplied by renewable resources (excluding transport) [86].

Table 3.4 shows some basic information about the so called *weak tools*.

Table 3.4 *Weak tools* basic features.

TOOL	Developer	Year	Availability	Brief Description
COMPOSE	Aalborg University, Denmark	2003	Free	Techno-economic energy-project assessment tool
RETScreen	Ministry of Natural Resources, Canada	1998	Free	Technical and financial feasibility study tool
TRNSYS	University of Wisconsin and University of Colorado	1975	Commercial	Transient systems simulation program
HYBRID2	University of Massachusetts, USA and NREL	Hybrid1 in 1994, Hybrid 2 in 1996	Free	Techno-economic simulation tool
SOMES	Utrecht University, Netherlands	1987	Commercial	Simulation and Optimization Model for renewable energy systems
HybSim	Sandia National Laboratories, US	-	Unknown	Economic and environmental evaluator
IPSYS	-	-	Unknown	Hybrid simulation modelling tool
RAPSIM	University Energy Research Institute, Australia	1996	Unknown, no modifications after 1997	Hybrid system model simulator
SOLSIM	Fachhochschule Konstanz, Germany	-	Not available	Simulation program
SOLSTOR	Sandia National Laboratories, US	Late 1970s and early 1980s	Not used now	Economics and optimization model
HySim	Sandia National Laboratories, US	Late 1980s	Not used after mid 1990s	Hybrid energy simulation model
HYSYS	Wind technology group(CIEMAT), Spain	Version 1.0 in 2003	Unknown	Hybrid simulation tool
Hybrid Designer	Energy and Development Research Centre, University of Cape Town, SA	-	Unknown	Simulation tool for applications in Africa's rural areas
Dymola / Modelica	Fraunhofer Institute for solar energy, Germany	-	Unknown	Programming language
ARES	Cardiff school of engineering, University of Wales, UK	-	Not available	Autonomous Renewable Energy system program
iGRHYSO	University of Zaragoza, Spain	-	Commercial, but current state is unknown	Optimization software
HYBRIDS	Solaris Homes	-	Unknown	Simulation tool
HYPORA	Pennsylvania State University, USA	-	-	Optimization tool
RESCOM	Imperial College, UK.	-	-	Residential Energy System Conceptual Optimization Model
DESDOP	Imperial College, UK.	-	-	District Energy System Design and OPtimization model
HYDROGEMS	Institute for Energy Technology	1995	Commercial, free for TRNSYS users	Set of hydrogen energy simulation tools

energyPRO	EMD International A/S company, Denmark	-	Commercial	Techno-economic design, analysis and optimization software package

3.1.3 Strong tools

The main sources for collecting information about *strong tools* are the reference websites of each tool or the following websites: [23]–[25].

3.1.3.1 HOMER energy

HOMER (Hybrid Optimization of Multiple Electric Renewables) is the most used and user-friendly computer model that assists in the design of micro-power systems and that facilitates the comparison of power generation technologies across a wide range of applications. Originally designed at the U.S. National Renewable Energy Laboratory (1993) for the village power program, HOMER is now licensed to HOMER Energy [87]. It is a commercial tool and its code cannot be modified by the users. A list of publications that involved HOMER is available from its homepage [87]. Moreover, online it is possible also to find other information, user guides, training manuals, flyers, etc. [88] [89] [90]–[93].

HOMER can perform simulation, optimization and sensitivity analysis of both off-grid and grid-connected power systems with any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, micro-turbines, fuel cells, batteries and hydrogen storage, serving both electric and thermal loads.

- The simulation process determines how a particular system configuration, a combination of system components of specific sizes and an operating strategy would behave in a given setting over a long period of time. The simulation process provides two purposes: firstly, it determines whether the system is feasible and so if it adequately serves the electric and thermal loads and satisfies any other constraints imposed by the user. Secondly, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. The simulation considers a one-year time-period using a minimum time-step of 1 min.
- The optimization process determines the best possible, or optimal, system configuration, which is the one that satisfies the user-specified constraints at the lowest total net present cost. Finding the optimal system configuration may involve deciding on the mix of components that the system should contain, the size or quantity of each component and the dispatch strategy the system should use. In the optimization process, HOMER simulates many different system configurations, discards the ones that do not satisfy the user-specified constraints), ranks the feasible ones according to total net present cost and presents the feasible configuration with the lowest total net present cost as the optimal system configuration.

- The sensitivity analysis reveals how sensitive the outputs are to changes in the inputs. Almost every numerical input variable in HOMER that is not a decision variable can be a sensitivity variable.

The main limitations of Homer are as follows [8]:

- HOMER allows only single objective function for minimizing the Net Present Cost (NPC) as such the multi-objective problems cannot be formulated. After optimization process HOMER makes chart for the optimized system configurations based on NPC and does not rank the hybrid systems as per levelized cost of energy.
- HOMER does not consider depth of discharge (DOD) of battery bank which plays an important role in the optimization of hybrid system, as both life and size of battery bank decreases with the increase in DOD. Therefore, the DOD should either be optimized or be included in sensitivity inputs of the Homer.
- HOMER does not consider intra-hour variability.
- HOMER does not consider variations in bus voltage.

A wide number of papers in literature talk about HOMER model. In particular, it has been used extensively for hybrid renewable energy system optimization and various case studies. Among others, it has been used to explore the role of gen-sets in small solar power systems in Sri Lanka [94], to simulate and analyse a PV-Wind-Diesel hybrid system [95], to find the best hybrid technology combination for electricity generation from a mix of renewable energy resources to satisfy the electrical needs in a reliable manner of an off-grid remote village, Palari in the state of Chhattisgarh, India [96], to perform an economic evaluation of a biomass gasification plant [97], to size stand-alone hybrid systems based on renewable energies and hydrogen [98], to assess the wind energy potential at individual locations in Ethiopia [99].

3.1.3.2 DER-CAM

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an economic and environmental model, a decision support tool for investment and planning of decentralized energy resources in buildings or micro-grids. It was developed at the Lawrence Berkeley National Laboratory, USA in 2000.

DER-CAM is not a simulation or a transient power flow model: it is a pure optimization tool whose objective function is to minimize the total energy cost and/or CO2 emissions, such that energy balance is preserved, technologies operate within physical boundaries and financial constraints are verified. The problem addressed is formulated as a mixed integer linear program (MILP): decision variables can be integer or continuous, objective function and constraints are linear and a global minimum is guaranteed.

On the basis of the different user needs, a specific versions of DER-CAM can be chosen:

- Full DER-CAM Web-Optimization Service: this version has been designed for researchers and experienced users who need sophisticated and detailed micro-grid analyses. It provides full micro-grid capabilities.

- Distributed Energy Resources Web Optimization Service (WebOpt) (under maintenance): this version is a simplified free version of DER-CAM and full DER-CAM capabilities and it has been designed for quicker and easier assessments. WeOpt does not provide all DER-CAM features and, in particular, it does not provide micro-grid capabilities.
- DER-CAM+ : this version has been designed for researchers and experienced users who need sophisticated and detailed micro-grid analyses. In fact, full micro-grid capabilities with power flow and locational analysis are included. DER-CAM+ differs from Full DER-CAM also for the fact that it is possible to perform a multi-node approach for both electrical and thermal networks. It is not an open source tool. DER-CAM+ has been presented and used in Mashayekh paper (2017) [100].

The technologies included are wind turbines, PV panels, solar thermal panels, conventional generators, CHP units, fuel cells, heat pumps, micro-turbines, absorption chillers. It is also possible to consider stationary storage, electric vehicles, heat storage or cooling storage.

DER-CAM has been used to find the optimal investment and scheduling of distributed energy resources with uncertainty in electric vehicle driving schedules [101], to deal with distributed generation with heat recovery and storage [102], to optimize distributed energy resources and build retrofits [103]. Lots of publications, user manuals, model presentations, training guides can be founded on the reference website [104].

3.1.3.3 LREM

LREM (Local Reference Electrification Model) was developed by a joint team from MIT and Comillas University in Madrid, supported by the Tata Trusts, Enel, and Iberdrola [105], [106]. It is an adaptation of the static, techno-economic model REM, which is suitable for large-scale modelling. LREM can be used as a modular package on its own, or it can work as an extension of REM. The purpose was to create a tool capable of producing detailed micro-grid designs suitable for the rural context. LREM was developed for two main purposes. Firstly, developments made to the operational design aspect of LREM will improve REM's generation designs. As such, REM's off-grid system designs will be more robust. The second major motivation was the lack of comprehensive, open source tools specific to rural micro-grid design. Oversizing results in excess expenses (which are highly undesirable in a resource constrained setting), while under-sizing leads to customer frustration. Both errors increase probability of failure for a micro-grid project.

Since it was designed especially for use in resource constrained environments, LREM aims to be simple to use, free and modular. As a matter of that, it can be broken into 4 main parts:

1. Inputs and Settings Building;
2. Generation Investment;
3. Network Design;
4. Results Output.

Given the expected demand and the inputs, LREM identifies the optimal generation mix of solar, diesel generation and storage which minimizes the total annuity. The generation assets sizing problem is based on complex, highly non-linear relationships between numerous variables. The approach taken by LREM is to decompose the generation investment problem into a hierarchical nested optimization structure, to which a structured direct search method is applied. The search space is split into two levels – one comprised of the generator sizes and the other comprised of the battery and PV bank. The generator size is the independent variable to be solved for in the upper “master” optimization problem. In the lower “slave” optimization problem, the generator size is a parameter and the independent variables are the PV and battery size. The split is done in this way because batteries and PV tend to function well in parallel. The search moves in the direction of steepest descent until it has located the lowest annuity within the total search space defined. Once the optimal generation mix and the simulated dispatch are given, LREM also estimates the associated costs and provides financial metrics.

The network design is done with the Reference Network Model (**RNM**), developed by IIT Comillas. RNM exists as two different models: the brownfield model, which attempts to build the new distribution network into the existing infrastructure, and the greenfield version, which assumes existing infrastructure is non-existent and therefore it is used for rural micro-grid design. RNM designs an optimal distribution low voltage network connecting the demand nodes to the generation site while respecting constraints. Given the low voltage network, RNM will decide if a medium or high (unlikely) voltage network is needed. The results provide a financial and technical design, including the specific conductor types and lengths in every part of the network. Obviously, RNM user must specify some inputs:

- A network catalog specifying the network component sizes, technical parameters and costs
- The geographic coordinates of the consumers (who will be connected at the low voltage level), including demand characteristics;
- The geographic coordinates of the generation site;
- Technical parameters of the generation site;
- Regions that cannot be trespassed can be specified.

Summing up, the outputs provided by LREM are: optimal generation mix, estimates of operational performance, optimal distribution network design and financial estimates.

The main information about LREM is taken from the reference websites and from the references [107], [108].

3.1.3.4 Micro-Grids py

Micro-Grids py is a free library of tools for the simulation and optimization of micro-grids, developed by University Of Liege, Energy Systems Research unit, Belgium together with University Mayor of San Simon, Energy Center, Bolivia; Sergio Balderrama and Sylvain Quoilin are the main developers. The documentation [109] and general information about this tool are found on GitHub platform [110]. It’s written in Python and it uses excel and text files as input and output data handling and visualization. The Micro-Grids py library main objective is to provide an open source alternative to the problem of sizing and dispatch of energy in micro-grids in isolated places. It help to find the optimal sizing of Lion-Ion batteries, diesel generators and PV panels in order to supply a demand with the lowest cost possible. For this objective the problem is express as a linear programming problem with the MILP option. by default, the time step is 1 hour and the optimization horizon is 1 year. Micro-Grids py calculates also the optimal dispatch from different energy sources, the net present cost (NPC) of the system for the project lifetime and the LCOE for the optimal system.

Micro-Grids py has been used in a work thesis [111] in order to perform sustainable energization of the village Toconao, Chile and in [112] for a feasibility study of PV/Li-Ion Battery in some Bolivian off-grid communities.

3.1.3.5 Multi Energy System py

Two students of the Polytechnic of Milano try to introduce and implemented, in their final thesis work [111], a new tool capable to perform a better optimization that satisfies both thermal and the electrical demand for rural communities: Multi Energy System. It is an open source model that is able to satisfy both the demands, considering the local energy requirements and the locally available renewable resources.

The peculiarity of the model lies on the two different approaches that the electrical and the thermal optimizations have: on the one hand the electrical load represents the entire demand of the village and a centralized configuration is thought to be installed; on the other hand a decentralized approach is applied dividing the entire thermal demand in classes and considering each class as a system that has to be optimized. In fact, for the thermal part, the model provides and sizes the nominal capacities of the installed technologies and the number of the solar collector units for each class. The synergy between the electrical and thermal part is very much clear comparing the respectively energy dispatches.

The considered technologies to satisfy the demands are PV panels, diesel generators, batteries, gas boilers, solar thermal collectors and hot water tanks for the provision of domestic hot water. Furthermore, an internal electric resistance element is included in the model of hot water tanks, thus allowing the electricity from the micro-grid to supply also thermal energy to charge the thermal storage.

The code is implemented in the Python language using the Pyomo Library. The input files are the electrical and the thermal demand, the photovoltaic energy, the solar collector energy and a data file where all parameters are defined. Finally, the program returns the electrical and thermal energy dispatch as well as the optimal configuration of both systems. The optimization of the model is performed through a Linear Programming (LP) formulation. This choice is dictated by the excessive computational time that an Integer or Mixed Integer Linear Programming (MILP) would require. This model is still under development and not available yet.

3.1.3.6 Calliope

Calliope is a framework to develop energy system models, with a focus on flexibility, high spatial and temporal resolution, the ability to execute many runs based on the same base model and a clear separation of framework (code) and model (data). The name derives from the idea of "multi-scale energy systems modelling" which leads to MUSES and thus Calliope. It is a freely available and open source tool implemented in Python and developed at the Department of Environmental Systems Science, ETH Zurich, Zürich, Switzerland. The main reference websites to find information about Calliope are the following: [113]–[115].

A Calliope model consists of a collection of text files that fully define a model, with details on technologies, locations, resource potentials, etc.

- Technology: a technology that produces, consumes, converts or transports energy;
- Location: a site which can contain multiple technologies and which may contain other locations for energy balancing purposes;
- Resource: a source or sink of energy that can (or must) be used by a technology to introduce into or remove energy from the system;
- Carrier: an energy carrier that groups technologies together into the same network, for example electricity or heat.

Calliope takes these files, constructs a pure linear optimization problem, solves it and reports back results. The objective function is to minimize total system cost, which results in the most techno-economically feasible system given the provided constraints.

The framework contains five abstract *base technologies*, from which new concrete technologies can be derived.

- Supply technologies can take a resource from outside of the modelled system and turn it into a specific energy carrier in the system. The model specifies one or more locations along with the technologies allowed at those locations.

Figure 3.1 Representation of Supply technology. From Calliope documentation.

- Transmission technologies can move energy of the same carrier from one location to another.

Figure 3.2 Representation of Transmission technology. From Calliope documentation.

- Conversion technologies can convert one carrier into another at the same location.

Figure 3.3 Representation of Conversion technology. From Calliope documentation.

- Demand technologies remove energy from the system.

Figure 3.4 Representation of Demand technology. From Calliope documentation.

- Storage technologies can store energy at a specific location.

Figure 3.5 Representation of Storage technology. From Calliope documentation.

Putting all of these possibilities together allows a modeller to specify as simple or as complex a model as necessary to answer a given research question.
Calliope also allows to model two kind of more complex technologies, called *plus technologies*:

- Supply plus technologies: allow a supply technology with internal storage of resource before conversion to the carrier happens. (CSP)

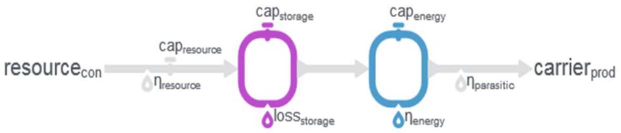


Figure 3.6 Representation of SupplyPlus technology. From Calliope documentation.

- Conversion plus technologies: allow for up to three carrier groups as inputs and up to three carrier groups as outputs. A carrier group can contain any number of carriers. (CHP)

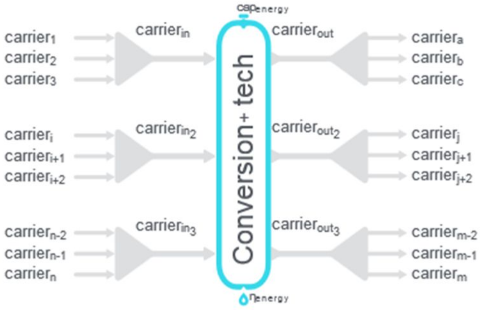


Figure 3.7 Representation of ConversionPlus technology. From Calliope documentation.

In Calliope Documentation [116] it is possible to find three simple tutorials that explain the key steps necessary to set up and run simple models and that show the key components of a Calliope model with which models of arbitrary complexity can be built.

The first tutorial builds a model for part of a national grid, exhibiting the following Calliope functionality:

- Use of supply, supply_plus, demand, storage and transmission technologies;
- Nested locations;
- Multiple cost types.

The second tutorial builds a model for part of a district network, exhibiting the following Calliope functionality:

- Use of supply, demand, conversion, conversion_plus, and transmission technologies;
- Use of multiple energy carriers;
- Revenue generation, by carrier export.

The third tutorial extends the second tutorial, exhibiting binary and integer decision variable functionality (extended an LP model to a MILP model). MILP functionality can be easily applied, but convergence is slower as a result of integer/binary variables.

A 2015 study [117] uses Calliope to compare three main possible generation technologies (renewables, nuclear, and fossil fuels with or without carbon capture and storage) from costs, emissions and energy security point of view. A second study [118] uses Calliope to deal with multiple decades of hourly wind and PV time series in energy models.

3.1.3.7 poli.NRG

poli.NRG (POLItecnico di Milano - Network Robust desiGn) is a novel software package for the robust design of off-grid electric power system developed at the Polytechnic of Milano. It can be freely downloaded [119], but it needs Matlab2016 to run, because the graphic user interface is not supported in previous versions. The main information about this tool is found in [112], [120].

Today, poli.NRG allows for the simulation of PV+BESS (battery energy storage system) system, but it is open to future improvements. It can be applied to any particular plant architecture (stand-alone systems, micro-grids, hybrid micro-grids, off-grid systems with possible main grid interconnection, etc.).

Poli.NRG is composed of four building blocks, related to different phases of the design procedure:

I. The *data inputs gathering block* provides a methodology to collect field data as regards weather condition and load demand.
II. The *inputs processing block* elaborates the inputs to obtain load and sources profiles over the entire lifetime of the plant. Daily load profiles are obtained by means of LoadProGen tool (Mandelli et al., 2016c) that is able to formulate different realistic daily load profiles starting from field data. LoadProGen is based on a stochastic approach and has been integrated in the Poli.NRG software package. Lifetime load profiles are generated assuming load evolution scenarios over the plant lifetime. RE source profiles are formulated according to specific models obtained from wheatear stations or from databases.
III. The *system modelling and simulation block* simulates different off-grid system configurations and evaluates the related techno-economic performances. The simulation engine investigates all the viable plant configurations considering the set of possible lifetime load profiles and the RE source profiles. This simulator has been implemented by the authors in an algorithm named OpSim (Operation Simulator), based on MATLAB. For each combination of PV and BESS size, OpSim provides techno-economic performance parameters: Loss of Load Probability (LLP), Net Present Cost (NPC) and Levelized Cost of Energy (LCOE).
IV. The *output formulation block* finds the most robust design for the targeted context through specific heuristic and mathematical optimization methods.

The goal of Poli.NRG is to size properly a micro-grid, addressing the lower NPC and satisfying the LLP (Loss of Load Probability) constraint. To do this, the software simulates all the possible combination, PV power and battery energy storage, that the designer decides to investigate. Therefore, the designer has the important role in setting the optimization space (PV and Battery range) in which all the simulations are implemented, to find out the best configuration among the simulated ones. Another option could be to select the automatic optimization space model of the software, in which the designer does not have to decide the optimization space.

The set of values required by Poli.NRG to set the optimization space are the following:

- Minimum PV power simulated [kW],
- Maximum PV power simulated [kW],
- PV power simulation step [kW],
- Minimum battery capacity installed [kWh],
- Maximum battery capacity installed [kWh],
- Battery capacity simulation step [kWh].

For all the possible combination (PV-Battery) implemented by the designer in the optimization space, Poli.NRG performs simulation in three principal steps:

1. Lifetime simulation;
2. Economic analysis;
3. Selection of the optimal micro-grid configuration.

This procedure is repeated for each of the scenario (demand curve) implemented. Each possible configuration (PV-Battery) is simulated over one year, with the assumption to be valid also for the subsequent year. The simulation time-step can be from 15 minutes to 1 hour. For all these combinations, an economic analysis is performed, to point out all the costs for the overall lifetime of the micro-grid. At the end, it is selected the micro-grid configuration (PV-Battery combination) that address the lowest NPC satisfying the LLP limit. This simulation methodology is repeated for all the considered load curves.

Finally, poli.NRG generates a graph (**Figure 3.8**) in which the optimal combinations PV-Battery are reported. The colour of each cell expresses a number of scenarios (load demand) for which that combination of PV-Battery has been selected as optimal. The colour of each cell indicates the number of simulations for which that configuration is selected as the optimal one among the overall simulations. The colour can vary from white (number of optimal solutions for the selected cell equal to zero) to red (number of optimal solutions for the selected cell equal to one).

It is important to notice that the best configuration (lower NPC satisfying LLP contain) is chosen only at the end, after all the combination are simulated.

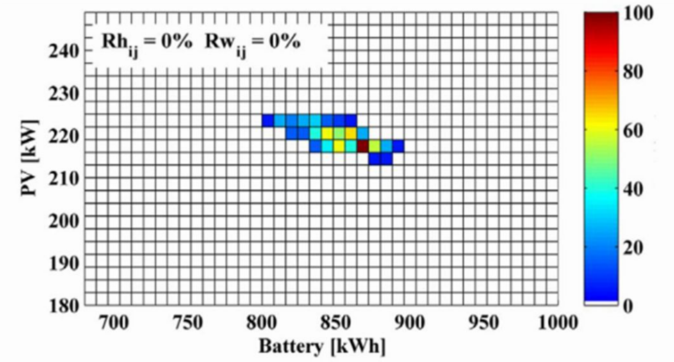


Figure 3.8 Example of poli.NRG output. From Sabatini and Tarantino Thesis .

Furthermore, an analysis of the results for each scenario is carried out to support the decision maker's choice (post-processing for decision-making). In particular, the obtained robust solutions are compared with respect to:

- The variation in the load consumption required by the customers;
- The variation on the system components' sizing due to the different scenario hypotheses assumed;
- The variation on the LCOE among the different scenarios given a fixed level of LLP.

The purpose of this step is to provide the decision-makers with more detailed information in order to identify the design of the off-grid power system that best suits the targeted context. Poli.NRG has been use to perform a sizing of a PV+BESS micro-grid system to supply power to a peri-urban area of Uganda [120] and to model battery storage systems and to implement it in a micro-grid design tools in Ngarenanyuki, Tanzania [121].

3.1.3.8 oemof

The Open Energy Modelling Framework (oemof) is a modular, free and open source tool for modelling and analysing multi-scale energy systems. It was developed by the Reiner Lemoin Institute (RLI), Germany. In the reference website [122] it is possible to find lots of publications, studies, applications and presentations [123]–[125] related to oemof. The documentation [126] and the open platform are available on [127].

oemof is implemented in Python and it provides base packages for energy system modelling and optimization. Oemof packages are organised in different levels, called libraries:

- oemof.network: it is the core of the libraries and it helps to create an energy system. It can be used to define energy systems as a network with components and buses: every component should be connected to one or more buses and it has to be added to its energy system; allowed components are sources, sinks and transformers *(transformers have any number of inputs and outputs, a sink has only an input but no output, a source has exactly one output but no input).*
- oemof.solph: linear optimization library that depends on the core libraries but does not provide interfaces to other oemof libraries. It is used to simulate or optimize multi-regional energy systems. The typical optimization is the dispatch optimization: the use of the sources is optimized to satisfy the demand at least costs. Solph library also provides a combined dispatch and investment optimization (based on investment costs you can compare the usage of existing components against building up new capacity).
- oemof.oututlib: the main purpose of this library is to collect and organize results. It depends on the core library but does not provide interfaces to other oemof libraries. Beside this, the outputlib provides some basic plot methods to create accurate plots.
- feedinlib: it is useful to calculate feedin time series for fluctuating renewable energy sources. It does not depend on any oemof interface and therefore can be used as stand-alone application.
- demandlib: it can be used to create load profiles for electricity and heat knowing the annual demand. It does not depend on any oemof interface and therefore can be used as stand-alone application.

For the communication between these libraries different interfaces are provided. The oemof libraries and their modules are used to build what is called an ‘application’ (app) which depicts a concrete energy system model or a sub-process of this model.

oemof includes and link the heat, power and mobility sector and describes energy systems with linear problems as well as with mixed-integer linear problems (MILP).
Recently, oemof has been used in [128] in order to deal with the integration aspects of high share of variable renewable energy sources (VRES) into the electric grid.

3.1.3.9 OSeMOSYS

OSeMOSYS is an open source modelling system for long-run integrated assessment and energy planning. It has been employed to develop energy systems models from the scale of continents down to the scale of countries, regions and villages. The first version of OSeMOSYS was made available in 2008 by the KTH Royal Institute of Technology, Sweden, while the first peer-reviewed publication describing its ethos and structure was available in 2011 [129]. OSeMOSYS is freely available and open source tool [130]. Recently, it has been translated into GAMS and Python programming languages, to reach a wider range of users from different backgrounds and levels of expertise. The main information about OseMOSYS can be founded in the following references [131]–[133].
Currently the OSeMOSYS code is available in two versions:

- The long code includes a full version of simple and user-friendly equations. It is easier to read and understand and it computes more variables. Therefore, it is particularly helpful to test modifications to the main code.
- In the short code , equations from the long version are put together. The outputs remain the same but the computational time is reduced. This code is not suitable for modifications because the equations are more complex and elaborated.

OSeMOSYS computes the energy supply mix (in terms of generation capacity and energy delivery) which meets the energy services demands every year and in every time step of the case under study, minimizing the total discounted costs. It can cover all or individual energy sectors, including heat, electricity and transport and has a user-defined spatial and temporal domain and scale. The energy demands can be met through a range of technologies which have certain techno-economic characteristics and draw on a set of resources, defined by certain potentials and costs. On top of this, policy scenarios may impose certain technical constraints, economic realities or environmental targets. OSeMOSYS is typically used for the analysis of energy systems looking over the medium (10-15 years) and long (50-100 years) term. In mathematical terms, it is a deterministic, linear optimization, long-term modelling framework. Mixed-integer linear programming may be applied for certain functions, like the optimization of discrete power plant capacity expansions.
Osemosys is divided in a series of component ‘blocks’ of functionality to easily modify and update the analysis. Each block includes series of equations with specification on the objective, costs, storage, capacity adequacy, energy balance, constraints, emissions. More blocks together form a customized model. In OSeMOSYS, like usually in linear programs, sets, parameters and variables are defined:

- Sets define the physical structure of a model, the time domain, the time split, the spatial coverage, the technologies and energy vectors to be considered, etc. They are: year, technology, time slice, fuel, emission, model operation, region, season, day type, daily time bracket, storage.
- Parameters are the user-defined numerical inputs to the model. Each parameter is a function of the elements in one or more sets. They are: global parameters, demands, performance, technology costs, storage, capacity constraints, activity constraints, reserve margin, RE generation target, emissions.
- Variables are the outputs computed by the code and they are functions of the elements in one or more sets. They are: demands, storage, capacity variables, activity variables, costing variables, reserve margin.

When developing a model in OSeMOSYS, the energy system is mapped to identify all the relevant technologies that will be involved, as shown in **Figure 3.9**. On the left, technologies categorized as primary energy resources are mapped. The lines represent energy carriers, e.g., crude oil, coal etc. Moving from the left to right the energy carriers are transformed through different technologies to ultimately meet a final demand for energy (services), presented by the technologies at the very right hand side of Figure.

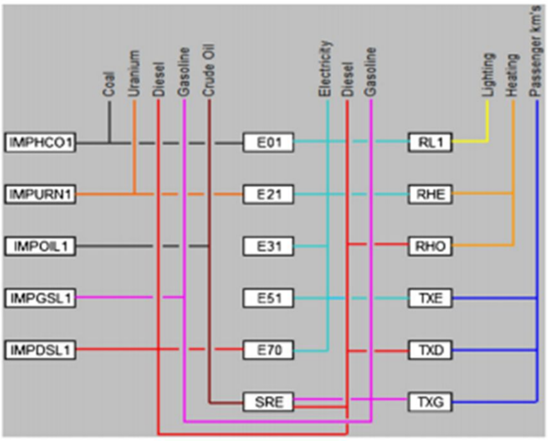


Figure 3.9 Example of OSeMOSYS energy system. From Howells paper.

OSeMOSYS has been used to model elements of smart grids in [134], to estimate the cost of energy access in the village of Suro Craic in Timor Leste [135], to perform analysis of investment opportunities in the African electricity supply sector [136], to find the minimum cost configuration of an urban transport system able to fulfill the mobility demand, under different technical and environmental constraints [137]. The study [138] presents a comparative analysis of the electricity export potential of Bolivia, considering modelling results carried out by the Bolivian government and those from OSeMOSYS SAMBA - South America Model Base.

3.1.3.10 URBS

URBS is a linear programming optimization model for capacity expansion planning and unit commitment for distributed energy systems, developed by the Chair of Renewable and Sustainable Energy Systems in the Technical University of Munich. Its name, Latin for city, stems from its origin as a model for optimization for urban energy systems. Since then, it has been adapted to multiple scales from neighbourhoods to continents. URBS is a free and open framework, implemented in Phyton [139]. The objective function is the minimization of the energy system cost in order to satisfy given demand time-series for possibly multiple commodities (e.g. electricity). By default, operates on hourly-spaced time-steps.
URBS consists of several model entities: commodities, processes, transmission and storage [140].

- Commodities are goods that can be generated, stored, transmitted and consumed. Commodities are defined over the tuple (site, commodity, type). Each commodity must be exactly one of the following four types:
  - Stock: buyable at any time for a given price;
  - supIm: supply intermittent stands for fluctuating resources;
  - Demand: usually, there is only one demand commodity called electricity, but multiple demands can be specified (e.g. electricity, space heating, process heat, space cooling);
  - Env: represents the amount of greenhouse gas emissions from processes.
- Input commodities are gas, coal, biomass, hydro and geothermal as well as the intermittent resources wind and solar. Electricity and CO2 emissions are modelled as output commodities.
- Processes describe conversion technologies from one commodity to another. They can be visualized like a black box with input(s) (commodity) and output(s) (commodity).
- Transmission allows instantaneous transportation of commodities between sites. It is characterized by an efficiency and costs, just like processes. Transmission is defined over the tuple (site in, site out, transmission, commodity). Storage describes the possibility to deposit a deliberate amount of energy in the form of one commodity at one time step, with the purpose of retrieving it later.
- Storage is defined over the tuple (site, storage, stored commodity).

URBS has been used to analyze the impact of restrictions on CO2 emissions on the power supply of Indonesia, Malaysia and Singapore in the year 2035 [141], to model and optimize an energy infrastructure at urban scale [142], to examine the role of grid extensions for the market effects of variable renewable energy generation from wind and sun in Europe [143], to minimize system cost for annualized investment, operation and maintenance costs as well as fuel costs for the complete system [144].

3.1.3.11 ficus

ficus is a (mixed integer) linear programming model for local multi-commodity energy systems, created at the Institute for Energy Economy and Application Technology, Technische Universität

München; the main developer is Dennis Atabay. Information and documentation [145] about this tool are found mainly on GitHub platform [146].

ficus is free and open framework, implemented in Phyton. Based on URBS and VICUS, it was developed as a model for optimizing energy systems of factories: it finds the minimum energy system cost to satisfy given demand time-series for possibly multiple commodities (e.g. electricity, heat). All resulting costs of the optimization are annualized.

ficus consists of several model entities: external imported/exported commodities, processes and storages.

- External imported/exported commodities are goods that can be imported or exported from/to “external sources” (e.g. the electric grid).
- Processes describe conversion technologies from one commodity to another. They can be visualized like a black box with multiple inputs (commodities) and multiple outputs (commodities). Processes are defined over the tuple (process , number, commodity, direction) that specifies the inputs and outputs for that process.
- Storage describes the possibility to deposit a deliberate amount of energy in form of one commodity at one time step, and later retrieving it. Storage is defined over the tuple (storage, number, stored commodity).

ficus has been used in 2017 to identify the cost-optimal configurations of specified energy-conversion processes and storage techniques to cover the factory's energy demand [147].

3.1.3.12 iHOGA

iHOGA (improved Hybrid Optimization by Genetic Algorithms) is a software developed in C++ by researchers of the University of Zaragoza (Spain) for the simulation and optimization of Hybrid Stand-alone Systems of Electric Power Generation based on Renewable Energies. The main information about this tool are taken by its reference site [148] and from the User Manuals [149][150]. There are two version of the software: Professional (PRO+) version, commercially available and with all options allowed, and Educational (EDU) version, freely available but with some restriction in the program features allowed. EDU version can only be used in training or educational fields. The use of EDU version is not allowed in engineering works, works of installations and, in general, in any case in which there are derived economic transactions. Nor is it allowed to be used in research projects such as the development of doctoral theses, etc.

iHOGA can simulate and optimize systems of any size and also systems connected to the AC grid, with or without own load consumption, and it can define different cases of Net Metering. The program also incorporates the possibility of selling electrical power to the AC grid (the remaining power that has not been consumed in the system), to buy the unmet load to the AC grid, as well as to sell the surplus hydrogen produced in the electrolyzer and stored in the tank.

The load (consumption) of the system can be:

- AC electrical load: electrical appliances that consume electrical energy directly in AC;
- DC electrical load: electrical appliances that consume electrical energy directly in DC;

- Hydrogen load (production of H2 for off-site consumption, for example to power electric vehicles based on fuel cells);
- Water consumption from a supply tank, water that will be previously pumped by an electric pump from a well or river to the tank.

The elements that can compose the hybrid system are:

- PV panels,
- Wind turbines,
- Hydraulic turbines,
- Batteries (lead-acid or lithium),
- Battery Charge Controller,
- Inverter (DC/AC converter), rectifier (charger, AC/DC converter) or inverter/charger (including inverter, rectifier and controller),
- Auxiliary generator (gasoline, diesel …),
- Fuel cell,
- H2 tank,
- Electrolyzer.

In general, the objective function of the optimization is the minimization of total system costs (or maximization of profits) over the system lifetime, transferred or updated to the initial moment of the investment (Net Present Cost, NPC). The program also allows multi-objective optimization, where not only economic optimization is considered, but also the simultaneous minimization of other variables that the user selects (equivalent CO2 emissions and/or unmet load). Since both objectives (cost and emissions or unmet load) are in many cases contradictory, when the system performs the multi-objective optimization it does not reach a single solution, but provides a wide range of solutions, some with better behaviour in terms of emissions or unmet load, others with better behaviour in terms of costs. The Human Development Index (HDI) and job creation can also be optimized in multi-objective.

iHOGA uses advanced models to accurately estimate the lifetime of the batteries, which are generally the most expensive components and that most replacements need. This implies that the estimation of the total net present cost of the system (NPC) can be obtained in a much more realistic way, being able to compare correctly between different combinations of components and control strategies and obtaining the real optimum.

iHOGA software includes advanced optimization algorithms (genetic algorithms), which implies the possibility of obtaining the optimum system using very low computational times. [2]. One problem with this methodology (GA) is that if the number of possible combinations is very high, the calculation time increases enormously and becomes unfeasible.

The software also includes simulation in time steps between 1 and 60 minutes, sensitivity analysis and probability analysis.

iHOGA has been used to perform a multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV–wind–diesel systems with batteries storage [151], to carry out an assessment of hybrid renewable power sources for rural electrification in Malaysia [152], to size stand-alone hybrid systems based on renewable energies and hydrogen [98].

3.1.3.13 INSEL

INSEL (Integrated Simulation Environment Language) was developed by University of Oldenburg, Germany at the end of 1980s. It is a commercial simulation model for renewable energy systems and efficient buildings, connected to the grid or as stand-alone systems. The main reference websites are [153], [154]. In order to increase the flexibility, INSEL is organized by blocks organized by categories (Time, Meteorology, Electricity etc.). Each block represents a system component and has a certain task. Blocks are then interconnected by users to define the energy system layout.

The components that can be simulated by this model are the following:

- PV modules,
- thermal collectors,
- wind turbines,
- diesel generators,
- batteries,
- charge controllers,
- heat pumps,
- hydrogen components,
- inverters.

This software has its own database of meteorological parameters of almost 2000 locations worldwide, photovoltaic systems, thermal systems and other devices hourly irradiance, temperature, humidity and wind speed data can be generated by using this software from monthly mean values for any given location and orientation. Users can specify the time step. Moreover, economic analysis is possible. A disadvantage of INSEL is that it does not perform system optimization.

INSEL has been used to compare some standard PV simulation programs [155], to design photovoltaic pumping systems for remote areas of developing countries [156], to try to reduce excess energy to a minimum using an energy effective demand side management [155].

3.1.3.14 H2RES

H2RES is a balancing tool that simulates the integration of renewable energy into energy-systems. The tool was developed in 2000 by the Instituto Superior Técnico in Lisbon, Portugal and the Faculty of Mechanical Engineering and Naval Architecture at the University of Zagreb, Croatia. H2RES is not yet sold to external users and it is available only internally. The main information about the tool are taken from [157].

The model is designed for balancing between hourly time series of water, electricity, heat and hydrogen demand, appropriate storages and supply over any user-defined period. The simulation of the electricity sector is based on criteria for the maximum acceptable proportion of intermittent and renewable-electricity in the power system. Using these criteria, H2RES integrates as much renewable/intermittent energy as possible into the energy-system, while either storing or discarding the rest of the renewable/intermittent output. Excess renewable-electricity can be stored. The main purpose of model is energy planning of islands and isolated regions which operate as stand-alone systems but it can also serve as planning tool for single wind, hydro or solar power producer connected to bigger power system. H2RES considers all forms of thermal generation except nuclear power, all renewable technologies except tidal power, all storage/conversion technologies except compressed-air energy storage, but only hydrogen vehicles are simulated in the transport sector. Costs are currently not considered in H2RES [7].

H2RES has been used to carry out an energy planning in the island of Mijet [158], to model biomass as a renewable energy source [159], to evaluate the use of hydrogen to store energy in the Porto Santo Island [160].

3.1.3.15 TOP-Energy

TOP-Energy is a toolkit for techno-economic analysis, simulation and optimization of decentralized industrial energy systems. The origins can be found around the turn of the millennium in doctoral theses and research projects at RWTH Aachen University. The simulation software has been actively developed since 2003 by a working group of the Society for the Advancement of Applied Computer Science (GFaI) in Berlin-Adlershof. The main information about TOP-Energy is found in the following websites [161], [162] and in the papers [22], [163]. It is commercially available (the price is reduced for non-commercial/academic use; it is free to try). TOP-Energy is used for a variety of other industrial processing apart from energy systems (heat, cooling, steam and compressed air, etc.). The process modelling language is based on Modelica.

TOP-Energy is built on a modular structure that maximizes its flexibility to adapt to different customer needs. It contains the following modules:

- Module eNtry for initial analysis: It checks the entered data on plausibility.
- Module eSim for simulation of energy systems: It allows to create, visualize and simulate complex energy systems.
- Module eVariant for evaluation of different variants: It is used for evaluating and summarizing the results of the simulations.
- Module eValuate for comparison and economic appraisal: It performs a comparative assessment of the considered variants on the basis of economic and environmental key figures.
- Module eSensitvity for sensitivity analysis: it is used to investigate the dependence on indicators based on changes in input variables and boundary conditions.
- Module eta: It is responsible for visualizing and editing time series.

The component or variant library, that the modules are equipped with, is being constantly expanded to satisfy the individual needs of the users. It is possible to easily integrate own components or adapt the existing ones.

TOP-Energy is also capable of performing calculations based on both financial and environmental parameters.

TOP-Energy has been used to find an efficient synthesis method for renewable energy systems that exploits synergies between heuristic and optimization-based approaches [164] and to optimize a solar driven energy and desalination system [165]. The paper [166] presents TOP-Energy as a software for simulation and analysis of industrial production processes tailored to engineers with little experience in simulation such as energy consultants or energy managers.

3.2 Comparative analysis of *strong tools* and discussion

From the following tables it is possible to have a more comprehensive, more direct and clearer overview about all of the so called *strong tools*. **Table 3.5** shows general information about reference websites, main developers and availability, while more specific generalities about geographical area, type of analysis, optimization logic, load demand type and technologies are reported in **Table 3.6** and **Table 3.7**. The last table (**Table3.8**) provides highlights concerning multi-year load option, horizon scenario timeframe, time resolution and topographic constraints.

Table 3.5 Information about reference website, original developer, availability, openness of *strong tools*.

TOOL	Reference Website	Original Developer	Availability	Open Source
HOMER	[87]	National Renewable Energy Laboratory, USA (1993)	Commercial	No
DER-CAM	[104]	Lawrence Berkeley National Laboratory, USA (2000)	Free	No
LREM	[105], [106]	Massachusetts Institute of Technology, USA	Free	Yes
Micro-Grids py	[110]	University of Liege, Belgium	Free	Yes
Multi energy system py	-	Polytechnique of Milan	Free	Yes
Calliope	[113]–[115]	ETH Zurich, Switzerland and University of Cambridge, UK	Free	Yes
poli.NRG	[119]	Polytechnique of Milan	Free	No
oemof	[122], [127]	Reiner Lemoine Institute, Germany	Free	Yes
OSeMOSYS	[130]	KTH Royal Institute of Technology, Sweden (2008)	Free	Yes
URBS	[139]	Technical University of Munich, Germany	Free	Yes
ficus	[146]	Technical University of Munich, Germany	Free	Yes
iHOGA	[148]	University of Saragoza, Spain (2005)	Commercial	No
INSEL	[153], [154]	University of Oldenburg, Germany (1986-91)	Commercial	No
H2RES	[157]	Instituto Superior Técnico, Lisbon (2000)	Internal use only	No
TOP-Energy	[161], [162]	RWTH Aachen University, Germany	Commercial	No

Table 3.6 Information about geographical area, type of analysis, mathematical approach, load demand of *strong tools*.

TOOL	Geographical Area	Type of Analysis	Mathematical Approach	Load Demand Type		
				Electricity	Thermal	Other
HOMER	Local, community	Simulation, optimization, sensitivity analysis	EO	x	x	Hydrogen
DER-CAM	Buildings and micro-grids	Optimization decision support tool	MILP	x	x	Hydrogen
LREM	Local	Optimization	EO	x	-	-
Micro-Grids py	Isolated areas	Optimization	LP and MILP	x	-	-
Multi energy system py	Isolated areas	Optimization	LP	x	x	-
Calliope	Multi scale	Optimization	LP and MILP	x	x	User-defined
poli.NRG	Isolated areas	Simulateon and optimization	EO	x	-	-
oemof	Multi scale	Optimization	LP and MILP	x	x	Transport
OSeMOSYS	Multi scale	Optimization	LP and MILP	x	x	Transport
URBS	Multi scale	Optimization	LP	x	x	User-defined
ficus	Local	Optimization	MILP	x	x	User-defined
iHOGA	Multi scale	Simulation, optimization and sensitivity analysis	GA	x	-	Hydrogen
INSEL	Multi scale	Simulation	-	x	x	Hydrogen
H2RES	Islands, isolated areas	Simulation	-	x	x	Hydrogen
TOP-Energy	Industrial scale	Simulation and optimization	MILP	x	x	User-defined

Table 3.7 Information about technologies of *strong tools*.

TOOL	**Hybrid mini-grid**									**Storage system**	
	Grid	**PV**	**Solar thermal**	**Wind**	**Hydro**	**Biogas**	**Biomass**	**Diesel gen.**	**Gas/LPG**	**Electrical**	**Thermal**
HOMER	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No
DER-CAM	No	Yes	Thermal collectors	Yes	No	No	No	Yes	No	Yes	Yes
LREM	No (REM)	Yes	No	No	No	No	No	Yes	No	Yes	No
Micro-Grids py	No	Yes	No	No	No	No	No	Yes	No	Yes	No
Multi energy system py	No	Yes	Thermal collectors	No	No	No	No	Yes	Yes	Yes	Yes
Calliope	User-defined									user-defined	
poli.NRG	No	Yes	No	No	No	No	No	Yes	No	Yes	No
oemof	User-defined									user-defined	
OSeMOSYS	Yes	Yes	CSP	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
URBS	User-defined									user-defined	
ficus	No	User-defined								user-defined	
iHOGA	Yes	Yes	No	Yes	Yes	No	No	Yes	No	Yes	No
INSEL	Yes	Yes	No	Yes	No	No	No	Yes	No	Yes	No
H2RES	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
TOP-Energy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 3.8 Information about multi-year load optimization, horizon scenario timeframe, topographic constraints, time resolution of *strong tools*.

TOOL	Multi-Year Load	Horizon Scenario Timeframe	Topographic Constraints	Time Resolution (by default)
HOMER	Yes (linear increment)	1 year	No	From 1 minute to 1 h
DER-CAM	No	1 year	Yes	From 1 minute to 1 h
LREM	No	1 year	Yes	1 hour
Micro-Grids py	No	1 year	No	User-defined (1 hour)
Multi energy system py	No	1 year	Yes	User-defined (15 minutes)
Calliope	No	1 year	Yes	User-defined (1 hour)
poli.NRG	Yes	Plant lifetime	No	1 minute
oemof	No	User-defined	Yes	User-defined (1 hour)
OSeMOSYS	Yes	1 year	Yes	User-defined (timeslice DAY)
URBS	No	User-defined	Yes	1 hour
ficus	No	1 year	Yes	15 minutes
iHOGA	No	1 year	No	User-defined (1 hour)
INSEL	No	1 year	No	User-defined
H2RES	No	Unlimited	No	User-defined (1 hour)
TOP-Energy	Yes	User-defined	Yes	User-defined

From this review, it is evident that there is a wide range of different energy tools available characterized by different features, characteristics and purposes. The following sections are useful to make a sum up.

3.2.1 Availability and Openness

HOMER, iHOGA, INSEL and TOP-Energy are commercial and closed tool. This means that if someone wants to download one of them, has to pay. Nevertheless, they are very used and widespread models. The remaining tools are freely available. Among them, only two are not also open: poli.NRG and DER-CAM. The other ones are open source models, meaning that users can modify and manage the code. H2RES has the peculiarity of being available only internally and so it cannot be accessible from external users (**Figure 3.10**).

Figure 3.10 *Strong tools* availability.

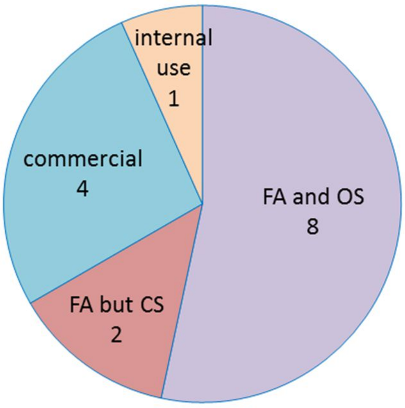
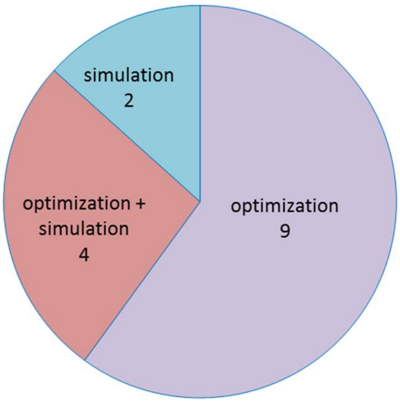


Figure 3.11 *Strong tools* type of analysis.



3.2.2 Geographical Coverage and Type of Analysis

Other important features to understand if a tool is suitable for a specific purpose are the type of analysis it performs and the geographical scale it covers.

In this review models which perform only energy optimization (DER-CAM, LREM, Micro-Grids py, Multi energy system py, Calliope, oemof, OSeMOSYS, URBS, ficus), only energy simulation (INSEL, H2RES) or both of them (HOMER, poli.NRG, iHOGA, TOP-Energy) are considered (**Figure 3.11**).

According to Van Beeck paper (1999) [167], optimization methodologies are used to optimize energy investment decisions endogenously (i.e., the results are directly determined by the input). The outcome represents the best solution for given variables while meeting the given constraints. Disadvantages are that optimization models require a relatively high level of mathematical knowledge and that the included processes must be analytically defined. Optimization models often use linear programming techniques.

According to the World Energy Conference (1986), simulation models are descriptive models based on a logical representation of a system and they are aimed at reproducing a simplified operation of this system. Simulation models are especially helpful in cases where it is impossible or extremely costly to do experiments on the system itself. A disadvantage is that simulation models tend to be rather complex. They are often used in scenario analysis. [167].

From geographical coverage pint of view, all the so called *strong tools* are suitable to consider small scale energy systems. Furthermore, some of them (Calliope, oemof, OSeMOSYS, URBS, iHOGA, INSEL) can be used to cover whatever area (multi-scale).

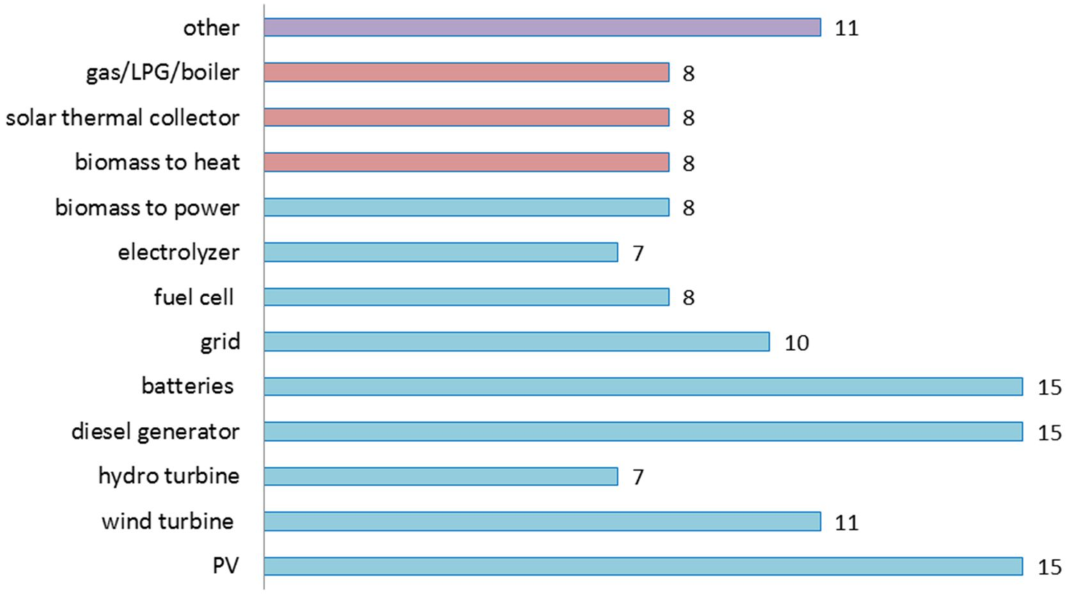
3.2.3 Technologies and Sectors

All the considered tools include PV, batteries and diesel generators. In particular, LREM, poli.NRG and Micro-Grids py model systems only with these three technologies with which they only cover the electric load. Multi energy systems py also includes solar thermal collectors and gas boiler, as a matter of fact it deal not only with the electric sector but also with the thermal one.

All the remaining tools (HOMER, DER-CAM, oemof, OSeMOSYS, iHOGA, INSEL, H2RES) include wind turbine in addition to PV, batteries and generators. Only HOMER, OSeMOSYS, iHOGA, INSEL and H2RES can add hydro turbines in the modeled system. Biomass technologies are included in HOMER, oemof, OSeMOSYS and H2RES and they can be used to produce both electricity and heat. Only LREM, DER-CAM, Micro-Grids py, Multi energy system py, poli.NRG and ficus do not allow the connection of the considered system to the existing grid.

For what concerns the thermal part, the technologies taken into account are solar thermal collectors (DER-CAM, Multi energy systems py, H2RES) , CSP (OSeMOSYS, H2RES), LPG/gas (Multi energy systems py, OSeMOSYS,) and other ones like for example CHP (HOMER, DER-CAM, oemof, OSeMOSYS, H2RES), heat pumps, nuclear, etc. (**Figure 3.12**).

Figure 3.12 *Strong tools* technologies.

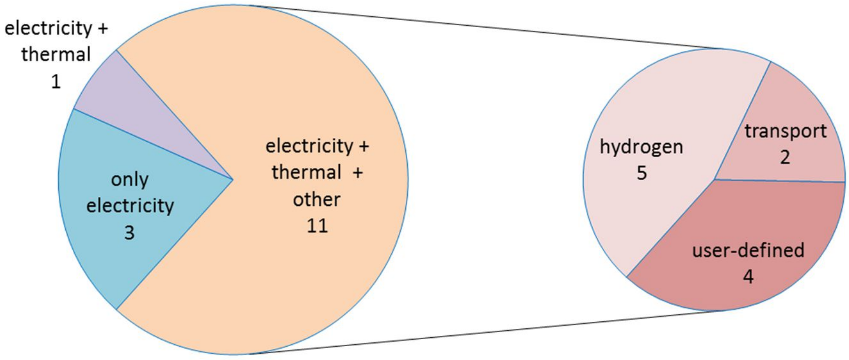


HOMER energy, DER-CAM, INSEL and H2RES consider not only electrical and thermal sectors and technologies but also those ones related to hydrogen. Precisely, they include electrolyzers and fuel cells. Also iHOGA takes into account hydrogen sector and technologies but it does not cover thermal load. OSeMOSYS and oemof consider electrical, thermal and transport sector.

All models include batteries as storage for electricity, but only DER-CAM, Multi energy system py, OSeMOSYS, H2RES and TOP-Energy consider also heat storage (**Figure 3.13**).

A particular specification must be made for Calliope, URBS and ficus: sectors and technologies, that can be selected from these models in order to create an energy system, are user-defined, meaning that users can consider and develop all the technology and sectors they need. This is because these tool are classified as frameworks and not just as models or softwares. Also in TOP-Energy it is possible to easily integrate own components or adapt the existing ones, even if it has a closed code and it is not categorize as a framework. Oemof is also a framework but, unlike the others, it has some default technologies and it is not structured with entities (commodities, processes, transmission, storage) that help to simplify code changes.

Figure 3.13 *Strong tools* sectors.



3.2.4 *Spatial Detail*

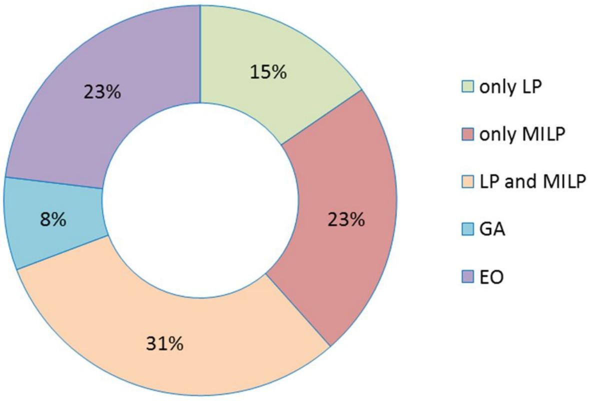
DER-CAM, LREM, Multi energy system py, Calliope, oemof, OSeMOSYS, URBS, ficus, TOP-Energy have also the possibility to consider a multi-node approach instead of just single-node approach, meaning that a detailed electrical and thermal network is provided. This is helpful to obtain the optimization of the micro-grid from both thermal and electrical point of view: power and thermal flow are specified and optimize for each node and the optimal pathway is found. Losses and constraints are also included.

In order to have detailed and optimized dispatch, the users must provide: load profiles disaggregated by fuel type and end-use (space heating, water heating, gas only, electricity only, cooling, refrigeration, etc.) in each node, electrical and thermal network parameters, including cost, and the topography of the ground.

3.2.5 Mathematical Approach

Another important feature that has been consider in this review is the optimization methodology lying behind the planning procedure of each tool.

Figure 3.14 *Strong tools* mathematical approach.



Some papers ([168]–[170]), talking about criteria to classify the mathematical approach of energy models, are analysed. The paper from which these authors seem to have based on is [171] by Yusta and Rojas-Zerpa. In accordance to it, decision criteria analysis is classified into seven sub-categories (classes of models): Linear Programming (LP), Multi-Criteria Decision Making (MCDM), Multi-Objective Programming(MOP), Non- Linear Programming (NLP), Dynamic Programming (DP), Enumerative Optimization (EO) and other (for example Genetic Algorithm).

Only four types of these optimization techniques are considered in this work: Linear Programming (LP), Mixed-integer Linear Programming (MILP), Enumerative Optimization (EO) and Genetic Algorithm (GA) (**Figure 3.14**).

LP is use to analytically optimize a linear objective function subject to linear constraints. Compared to others, it is a computationally fast and easy-to-solve method. Nevertheless, in a few cases, it requires significant simplifications, for real physical phenomena to be represented by linear relationships. For this reason sometimes Mixed Integer Linear Programming is preferred. In fact, it involves linear objective function and constraints but integer variables. In this way the analysed system is closer to reality. The problem with this type of programming is the complex mathematical equations and the high the computational time. Among the reviewed tools, URBS and Multi energy system py use only LP, DER-CAM, ficus and TOP-Energy use only MILP, while Micro-Grids py, Calliope, oemof and OSeMOSYS use both LP and MILP.

EO calculates numerically the optimal solutions based on one or more objectives. Differently from LP and MILP that consider an objective function o be maximized or minimized analytically, EO is based on a numerical and heuristic optimization that usually follows these following steps [168]:

I. the definition of a problem space (which is finite, discrete and includes all the potential solutions);
II. the numerical evaluation at every, or almost every, discrete point in the space of the value of the function to be optimized;
III. the enumeration of all the candidate solutions that respect the imposed constraints;
IV. the identification of the candidate solution(s) with the minimum or maximum value(s) of the function to be optimized.

HOMER, poli.NRG and LREM are examples of tools that use Enumerative Optimization to find the best solution.

Genetic Algorithm is used by iHOGA. It is an advanced optimization algorithms and the most popular type of Evolutionary Algorithm. GA seeks the solution of a problem in the form of strings of numbers (traditionally binary, although the best representations are usually those that reflect something about the problem being solved) by applying operators such as recombination and mutation (sometimes one, sometimes both) [172]. It allows to obtain the optimum system using very low computational times. One problem with this methodology is that if the number of possible combinations is very high, the calculation time can increases enormously and becomes unfeasible.

3.2.6 User-friendliness and Flexibility

User-friendliness is an indication of accessibility, ease to use, operation and understanding of a tool. There are two ways to check if a tool is user-friendly: the documentation level, by means of straightforward guides in jargon-free language, and the presence of a simple and direct Guide User Interface (GUI).

HOMER, DER-CAM, poli.NRG, iHOGA, INSEL, H2RES, TOP-Energy are characterized by having a detailed and clear GUI . It this way, it is easy for a user, who has never used the model, learning in short time how to manage the model. On the contrary, tools like Calliope, oemof, URBS, ficus, OSeMOSYS, Micro-Grids py, are more complex and difficult to use and to learn because they are open source models and the user should have enough knowledge and skills in programming in order to be able to understand and to modify the code. Nevertheless, they have the great vantage to be flexible for any use and need because they have lot of freedom.

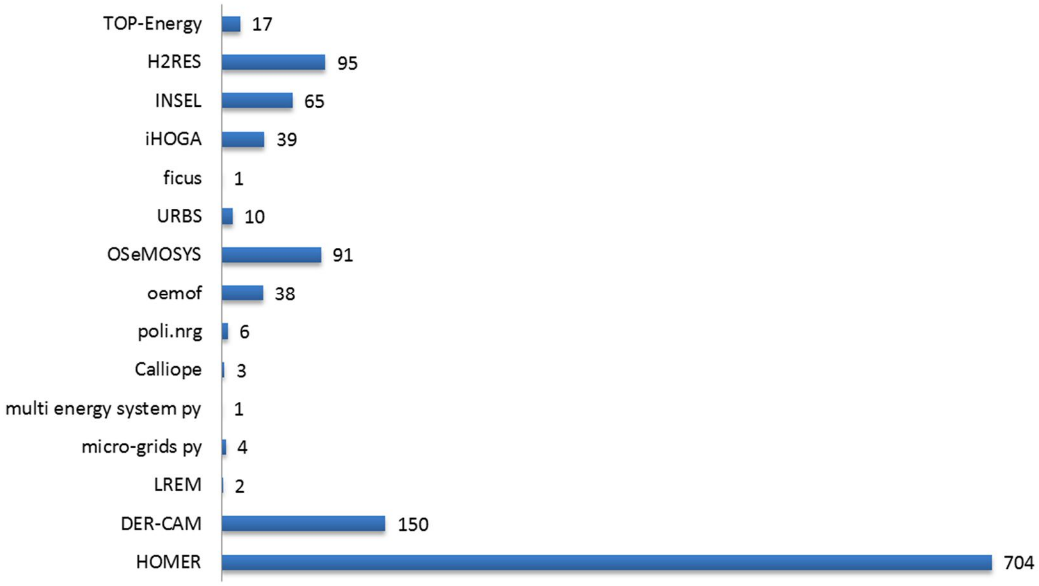
Calliope, DER-CAM, HOMER, iHOGA, Micro-Grids py, oemof, OSeMOSYS, URBS, ficus are provided with a great documentation. It is possible to download user manuals, guides, training sessions, tutorials, presentations from the reference websites.

3.2.7 Citations in Literature

In order to understand the level of diffusion of each tool, a deep analysis is carry out to check how much models have been used or cited in literature. The way this analysis is performed is explained in the section 2.2 of methodology.

The results are shown in **Figure 3.15**, where the number of times a model is mentioned in literature is reported.

Figure 3.15 *Strong tools* citations in literature.



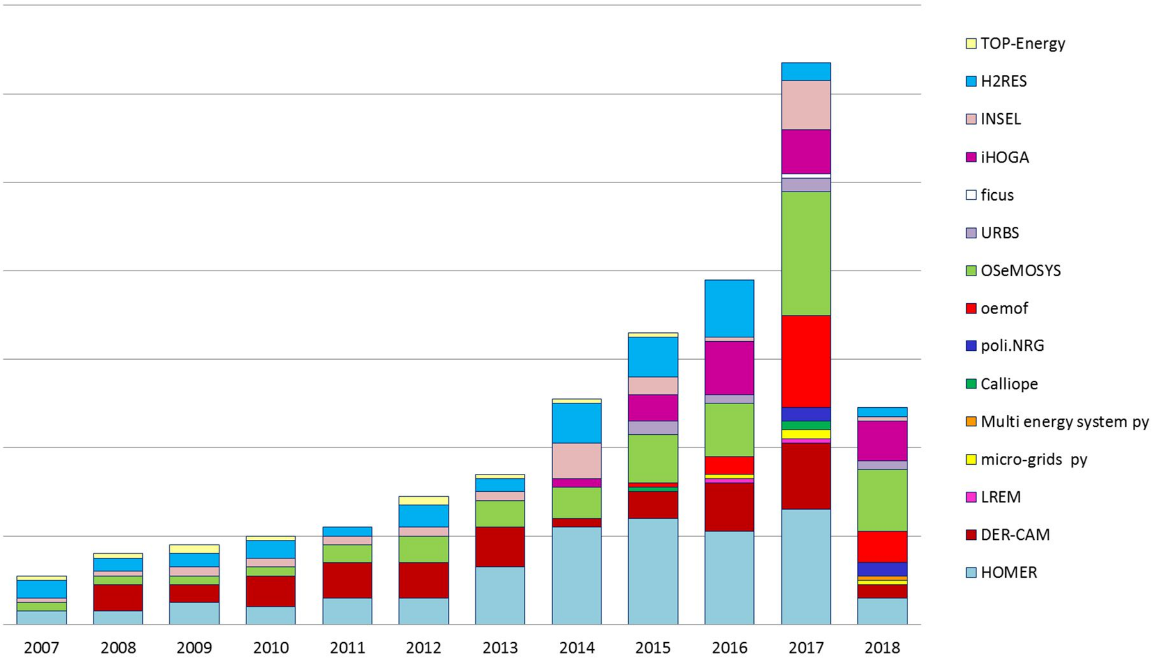
It is possible to immediately note that HOMER is the most cited tool, followed by DER-CAM, OSeMOSYS and H2RES. Even INSEL, iHOGA and oemof have a good number of citations. This is an indication also for knowing the level of diffusion and use of the model. On the contrary, TOP-Energy, LREM, Micro-Grids py, Multi energy system py, Calliope, poli.NRG, URBS and ficus are cited very few times. Despite this, oemof, Calliope, URBS, ficus, are very used. Probably, this result is due to the fact that they are frameworks more than models and they have a platform where users can host and review code, manage projects and build software, and this kind of use of the model is not taken into account in the literature.

For this reason, another type of analysis is made in order to check how the state of each tool is changed through years and to understand which are the tools that are more used and mentioned nowadays. The same analysis as before is carried out but it is performed year by year. Ten years are taken into account, from 2007 to today (**Figure 3.16**).

In general, the trend is increasing, meaning that the number of citations in literature is growing through years and, accordingly, the interest towards energy modelling tools. Note that in 2018 only citations of a part of the year are taken into consideration.

Specifically, H2RES, TOP-Energy, DER-CAM, HOMER, INSEL, OSeMOSYS developed since the first years, while ficus, URBS, iHOGA, poli.NRG, Calliope, Multi energy systems py, Micro-Grids py, LREM, oemof developed in the last years. This means that recently more attention and interest is given on frameworks and on open source models, even if the other types of energy softwares are still used.

Figure 3.16 *Strong tools* citations in literature through years.



3.3 SWOT of *strong tools* and discussion

What emerged from the previous analysis could mean that nowadays there are two types of users, characterized by different purposes: the one that focuses his attention on the research field and chooses open energy models or frameworks, and the other one that prefers to use tools for implementation, comparison, consultancy, or assessment.

In order to help to understand which is the model best suited for a particular aim, weaknesses and strengths of each tool are highlighted in the SWOT matrix reported in **Table 3.9**.

Table 3.9 SWOT matrix of *strong tools*.

TOOL	INTERNAL		EXTERNAL	
	STRENGHTS	WEAKNESSES	OPPORTUNITIES	THREATS
HOMER	Optimization, simulation, sensitivity analysis; Robust design; Multi sector; Partially allows multi-year optimization;	Find the right optimization space (EO); Multi-year optimization allows only linear load increment;	User-friendly; Lot of documentation available;	Commercial; No open source; Requires detailed and quality input data;
DER-CAM	Optimization; MILP; Multi sector; Multi-node approach;	Outputs and efficiencies are considered as constant during the lifetime of equipment;	Free; User-friendly; Lot of documentation available;	No open source; GAMS needed; Requires detailed and quality input data;

LREM	Optimization; Robust design; Multi-node approach; Optimization of mini-grid with RNM;	Find the right optimization space (EO); Only electricity sector; No extension to existing grid (REM needed); No multi-year optimization;	Free; Open source;	Little documentation available; Detailed and quality input data;
Micro-Grids py	Optimization; LP and MILP;	Only electricity sector; No extension to existing grid; No MILP by default; No multi-year optimization;	Free; Open source; Lot of documentation available;	Phyton needed; Programming skills needed; Still under development; Little documentation available;
Multi energy system py	Optimization; Electricity and thermal sectors; Multi-node approach;	Only LP; No extension to existing grid; No multi-year optimization;	Free; Open source;	Phyton needed; Programming skills needed; Still under development; Little documentation available;
Calliope	Optimization; LP and MILP; High flexibility; Multi sector; Multi-node approach;	No MILP by default; Multi-year optimization still under development;	Free; Open source; Lot of documentation available;	Phyton needed; Programming skills needed;
poli.NRG	Optimization, simulation; Robust design; Multi-year optimization;	Find the right optimization space (EO); Only electricity sector; No extension to existing grid;	Free; User-friendly;	No open source; Matlab16 needed; Little documentation available; Requires detailed and quality input data;
oemof	Optimization; LP and MILP; High flexibility; Multi sector; Multi-node approach;	no MILP by default; No multi-year optimization;	Free; Open source; Lot of documentation available;	Phyton needed; Programming skills needed;
OSeMOSYS	Optimization; LP and MILP; Multi sector; Multi-year optimization;	No MILP by default; Low spatial and temporal resolution;	Free; Open source; Lot of documentation available;	GAMS needed; Programming skills needed;
URBS	Optimization; High flexibility; Multi sector; Multi-node approach;	Only LP; No multi-year optimization;	Free; Open source; Lot of documentation available;	Phyton needed; Programming skills needed;
ficus	Optimization; MILP; High flexibility; Multi sector; Multi-node approach;	No extension to existing grid; High computational time;	Free; Open source; Lot of documentation available;	Phyton needed; Programming skills needed;
iHOGA	Optimization, simulation, sensitivity analysis; Electricity and hydrogen; Partially allows multi-year optimization;	No thermal sector; Multi-year optimization allows only linear load increment;	User-friendly; Lot of documentation available;	Commercial; No open source; Developed in C++; Requires detailed and quality input data;
INSEL	Multi sector;	No optimization;	User-friendly; Good documentation available;	Commercial; No open source;
H2RES	Multi sector;	No optimization;	User-friendly;	Only internal use; No open source; Little documentation available;

TOP-Energy	Optimization, simulation; MILP; Flexible; Multi sector; Multi-node approach;	Flexibility does not come from the possibility to modify the code; High computational time;	User-friendly;	Commercial; No open source; Little documentation available;

Among the characteristics stated as positive in the SWOT matrix for a tool which purpose is to model multi-energy systems in rural areas, there are:

- freely availability for guarantee accessibility and affordability;
- open source code to ensure:
  - adaptability (each rural areas has different local sources, different needs, different conditions),
  - knowledge transfer (it is important not only provide the right micro-grid, but also to show local people how to do it and to inform how to use and to maintain it),
  - transparency;
- multi-sectorial and synergies between sectors: thermal sector, and not only electrical one, is important in rural areas where people still relay on traditional biomass (cooking, space and water heating);
- multi node approach: it gives a better optimization of the network and an accurate dispatch of the energy flows. The only drawback is that this option requires detailed and quality input data;
- user-friendliness in order to simplify the understanding and the use of the tool;
- flexibility to have a wide range of possibilities and options to find the most suited multi-energy system for each different specific context. Obviously, this property implies complexity and requires good programming skills;
- lot of documentation available in order to learn quickly how the tool works;
- possibility to switch between MILP and LP to obtain more realistic and precise results, without compromising too much the computational time;

From the SWOT analysis it is possible to notice that the considered tools can be divided into two groups, as to confirm what said before about the two types of users, characterized by different purposes. This split comes from the fact that, generally speaking, some features always go along with other ones. For example openness means also flexibility and programming ability, while closeness is related to user-friendliness and rigidity. The tools included in the first group are Calliope, oemof, OSeMOSYS, URBS, ficus, Micro-Grids py and Multi energy system py and they can be selected by user oriented towards research purposes. On the contrary, HOMER, iHOGA, INSEL and H2RES belong to the second group and they can be chosen when assessment, implementation, comparison, consultancy are the main aims of the user. Then, there are some tools that are “in the middle” because they have characteristics belonging from both groups: DER-CAM and poli.NRG are freely available but they are not open, so they are easier to use but not flexible. TOP-Energy is characterized by a lot of flexibility which however does not come from the openness and the availability. In fact, it is a commercial and closed tool. Moreover it is a user-friendly software. LREM especially focuses on micro-energy system modelling in rural areas but is has not the structure of a framework and, even if it is a freely available and open source model, it is not suitable for modifying and adapting of the code.

Nevertheless, what is important to highlight is that there is not a fixed and unique rule for choosing the ideal tool for a rural context: the aim of this work is not to suggest the best energy model, but to provide criteria to help to identify the most suitable one according to user needs and purposes.

Moreover, from the review it is possible to state that for years HOMER has been considered by the literature the state of the art of the local energy system modelling. Despite it has lot of positive aspects, HOMER has also lots of limitations, such as the commercial aspect, the low accessibility, the narrow range of modelling options, the weak synergy between thermal and electrical sectors, etc. Additionally, HOMER, together with other models developed in the earlier years, were built for the needs and the aims of that period. Nowadays the attention is shifted towards new purposes and towards the solution of new problems: the current global climate change, the decreasing of energy resource stocks, the decision to exploit renewable energy sources, the willingness to provide access to energy to all, the energy security aspiration, etc.

All this brings the research and the literature towards new energy system modelling tools, more flexible, transparent and fully accessible. For these reasons tools like Calliope, oemof and Multi energy system py are starting to take hold.

In order to help in the choice of the most suitable tool, the following tables are reported below. They can help to make a comprehensive and direct idea of the characteristics of each *strong tools*.

HOMER	
	Hybrid Optimization of Multiple Electric Renewables
Original developer	National Renewable Energy Laboratory, USA
Reference website	https://www.homerenergy.com/
Availability	Commercial No open source
Type of analysis	Simulation, optimization, sensitivity analysis
Geographical coverage	Local, community
Load demand type	Electricity, thermal, hydrogen
Technologies	PV, wind turbines, small hydro, biomass, genset, cogeneration, micro-turbines, fuel cells, batteries, electrolyzers
Mathematical approach	Enumerative optimization
Time resolution	*From 1 min to 1 hour*

Table 3.10 HOMER basic features.

DER-CAM	
	Distributed Energy Resources Customer Adoption Model
Original developer	Lawrence Berkeley National Laboratory, USA
Reference website	https://building-microgrid.lbl.gov/projects/der-cam
Availability	Free; No open source
Type of analysis	Optimization
Geographical coverage	Buildings and micro-grids
Load demand type	Electricity, thermal, hydrogen
Technologies	PV, wind turbines, solar thermal panels, combustion engines, fuel cells, micro-turbines, CHP, heat pumps, batteries, electric vehicles, heat storage, cold storage
Mathematical approach	MILP
Time resolution	*From 1minute to 1hour*

Table 3.11 DER-CAM basic features.

LREM	
	Local Reference Electrification Model
Original developer	Massachusetts Institute of Technology, USA Comillas University, Spain
Reference website	https://tatacenter.mit.edu/portfolio/rem-a-planning-model-for-rural-electrification/ https://www.iit.comillas.edu/technology-offer/rem
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Local
Load demand type	Electricity
Technologies	PV, genset, batteries
Mathematical approach	Enumerative optimization
Time resolution	*1 hour*

Table 3.12 LREM basic features.

iHOGA	
	improved Hybrid Optimization by Genetic Algorithms
Original developer	University of Saragoza, Spain
Reference website	https://ihoga.unizar.es/en/
Availability	Commercial; No open source
Type of analysis	Simulation, optimization, sensitivity analysis
Geographical coverage	Multi-scale
Load demand type	Electricity, hydrogen
Technologies	PV, wind turbines, hydraulic turbine, auxiliary generator, fuel cell, H2 tank, electrolyzer, batteries
Mathematical approach	Genetic algorithm
Time resolution	*From 1 minute to 1 hour*

Table 3.13 iHOGA basic features.

oemof	
	Open Energy MOdelling Framework
Original developer	Reiner Lemoine Institute, Germany
Reference website	https://oemof.org/
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Multi-scale
Load demand type	Electricity, heating, transport
Technologies	User-defined
Mathematical approach	LP and MILP
Time resolution	*User-defined*

Table 3.14 oemof basic features.

OSeMOSYS	
	Open Source energy MOdeling SYStem
Original developer	KTH Royal Institute of Technology, Sweden
Reference website	http://www.osemosys.org/
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Multi-scale
Load demand type	Electricity, thermal, transport
Technologies	PV, CSP, wind turbines, genset, mini hydro, nuclear power plant, CHP, storage technologies
Mathematical approach	LP and MILP
Time resolution	*User-defined (time-slice)*

Table 3.15 OSeMOSYS basic features.

Calliope	
	Energy modelling framework
Original developer	ETH Zurich, Switzerland
Reference website	https://www.callio.pe/ https://calliope.readthedocs.io/en/stable/
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Multi-scale
Load demand type	User-defined
Technologies	User-defined
Mathematical approach	LP and MILP
Time resolution	*User-defined*

Table 3.16 Calliope basic features.

poli.NRG	
	Robust energy designer
Original developer	Politecnico di Milano, Italy
Reference website	https://www.dropbox.com/sh/7wbbvwde2ldcmza/AADPenaN0E-F71iF6DOpA17da?dl=0
Availability	Free; No open source
Type of analysis	Simulation and optimization
Geographical coverage	Small scale (off-grid systems)
Load demand type	Electricity
Technologies	PV, genset, batteries
Mathematical approach	Enumerative optimization
Time resolution	*1 minute?*

Table 3.17 poli.NRG basic features.

URBS	
	Energy modelling framework
Original developer	Technical University of Munich, Germany
Reference website	https://github.com/tum-ens/urbs https://urbs.readthedocs.io/en/latest/
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Any size
Load demand type	User-defined
Technologies	User-defined
Mathematical approach	LP
Time resolution	*1 hour*

Table 3.18 URBS basic features.

ficus	
	Energy system optimization model
Original developer	Technical University of Munich, Germany
Reference website	https://github.com/yabata/ficus http://ficus.readthedocs.io/en/latest/
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Local
Load demand type	User-defined
Technologies	User-defined
Mathematical approach	MILP
Time resolution	*15 minutes*

Table 3.19 ficus basic features.

Micro-Grids py	
	Library of tools
Original developer	University of Liege, Belgium
Reference website	https://github.com/squoilin/MicroGrids
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Isolated regions
Load demand type	Electricity
Technologies	PV, genset, batteries
Mathematical approach	LP
Time resolution	*1 hour*

Table 3.20 Micro-Grids py basic features.

Multi energy system py	
Original developer	Politecnico di Milano, Italy
Reference website	-
Availability	Free; Open source
Type of analysis	Optimization
Geographical coverage	Isolated regions
Load demand type	Electricity, thermal
Technologies	PV, solar thermal collectors, gas boiler, genset, storage technologies
Mathematical approach	LP and MILP
Time resolution	*15 minutes*

Table 3.21 Multi energy system py basic features.

INSEL	
	Integrated Simulation Environment Language
Original developer	University of Oldenburg, Germany
Reference website	http://www.insel.eu/en/home_en.html
Availability	Commercial; No open source
Type of analysis	Simulation
Geographical coverage	Any size
Load demand type	Electricity, thermal, hydrogen
Technologies	PV, solar cooling, wind turbines, genset, batteries, heat pumps, hydrogen components
Mathematical approach	-
Time resolution	*User-defined*

Table 3.22 INSEL basic features.

H2RES	
	Tool for integration of renewable energy into energy systems
Original developer	Instituto Superior Técnico, Lisbon
Reference website	http://h2res.fsb.hr/index.html
Availability	Only internal use; No open source
Type of analysis	Simulation
Geographical coverage	Isolated regions
Load demand type	Electricity, thermal, hydrogen, water
Technologies	All forms of thermal generation (except nuclear), all renewable technologies (except tidal power), all storage and conversion technologies (except compressed-air energy storage)
Mathematical approach	-
Time resolution	*User-defined*

Table 3.23 H2RES basic features.

TOP-Energy	
	Energy framework
Original developer	RWTH Aachen University, Germany
Reference website	https://www.top-energy.de/en.html
Availability	Commercial; No open source
Type of analysis	Simulation and optimization
Geographical coverage	Industrial scale
Load demand type	User-defined
Technologies	User-defined
Mathematical approach	MILP
Time resolution	*User-defined*

Table 3.24 TOP-Energy basic features.

Conclusions

The scope of this thesis work is to provide a sort of library of energy modelling tools in order to make easier the selection of one model with respect to specific purposes and characteristics of the energy system which is intended to take into consideration. In particular, the focus is on tools suitable for multi energy planning in rural areas.

The starting point of the work is a deep and rigorous literature review of the most useful existing and using tools in order to find the ones most appropriate for the main aim. Therefore, at the beginning, a lot of models has been found and analysed: they differentiated for example for the regions they analyse, the technologies and the sectors they consider, the objectives they fulfil, the type of analysis they perform.

Then, the found tools are divided into three groups depending on how much they meet the requirements:

- The ones that do not fulfil at all the requests, named *out of scope tools*. They for example focus on large scale systems or are included in different categories than those which perform the system modelling, such as power market or demand driven energy models. Since they are out of interest for the purpose of this thesis, only a rough description is provided. They are: AEOLIUS, BALMOREL, BCHP screening Tool, E4cast, EMCAS, EMINENT, EMPS, EnergyPLAN, ENPEP-BALANCE, GTMax, IKARUS, INFORSE, Invert, LEAP, MARKAL/TIMES, Mesap PlaNet, MESSAGE, MiniCAM, NEMS, ORCED, PERSEUS, PRIMES, ProdRisk, RAMSES, SimREN, SIVAEL, STREAM, UniSyD, WASP, WILMAR Planning Tool.
- The ones called *weak tools,* because they cannot satisfy all the characteristics required for a good rural energy planning or because they are no longer used or modified since long time and, consequently, there are not enough material or information about. Therefore, a brief description of the main features of this tools is performed. They are: HYBRID2, iGRHYSO, HYBRIDS, RAPSIM, RETScreen, SOMES, SOLSTOR, HySim, HybSim, IPSYS, HySys, Dymola/Modelica, ARES, TRNSYS, SOLSIM, Hybrid Designer, HYPORA, RESCOM, DESDOP, COMPOSE, energyPRO, HYDROGEMS.
- The ones considered the most suitable and the most complete to ensure a correct energy system modelling in rural areas. They are named *strong tools* and a deep and complete description of them is carried out. They are: HOMER, H2RES, INSEL, iHOGA, DER-CAM, LREM, oemof, OSeMOSYS, Calliope, URBS, ficus, poli.NRG, TOP-Energy, Micro-Grids py, Multi energy system py.

After highlighting the most focusing and interesting tools for the scope of this work, a section is dedicated to a comparative analysis between them. In particular:

- it indicates if a model is freely available or commercial, if it is possible to modify its code, if it performs only simulation, only optimization or both of them.
- Furthermore, the comparison shows the energy sectors and the technologies included in each tools and the mathematical approach used to carry out the optimization of the energy system considered. In this regard, the optimization techniques taken into account by the considered tools are Linear Programming, Mixed-Integer Linear Programming, Enumerative Optimization and Genetic Algorithm. In particular, the aspect that the thesis wants to highlight is the importance of the Mixed-Integer Linear Programming because it allows to obtain more precise and realistic results than the other options. Moreover, including technologies covering both electrical and thermal sectors is crucial in such context where people still rely on harmful and polluting biomass for cooking, heating and lighting.
- Additionally, specifications on spatial detail are considered also relevant because multi-node approaches are preferable to single-node applications since it allows to better optimize the micro-grid from both thermal and electrical point of view.
- Another important concept faced in the comparative analysis is the importance of flexibility and the user friendliness. The former is strictly related to the openness because the possibility to modify the code makes the tools adaptable to any needs and use. This freedom has, however, also a drawback because it requires high programming skills. The latter is an indication of the level of documentation available but also of the simplicity in using the model.
- Lastly, in order to realize how much a tool is used and widespread, a deep analysis on how many times it is cited in literature is produced. It is suddenly evident that HOMER is the most cited tool, followed by DER-CAM, OSeMOSYS, H2RES, INSEL, iHOGA and oemof. The remaining models, TOP-Energy, LREM, Micro-Grids py, Multi energy system py, Calliope, poli.NRG, URBS and ficus, appear very few times. In order to better understand why, another type of evaluation is carry out: the number of appearances in literature is now considered year by year. In this way it is possible to notice that the tools that previously seemed not to be considered, because cited very few times, are the ones developed in the last years. Probably, their condition is due to the fact that the interest towards this type of model was born only recently. In fact, they are open frameworks more than models, meaning that they have a platform where users can host and review code, manage projects and build software. This kind of use of the model is not taken into account in the literature, but the need of this type of tools is growing in the recent past in which the necessity to energize rural areas of developing countries is more and more a priority. For these reasons, transparency, affordability, accessibility, knowledge transfer and adaptability are now the main features required by a model aiming to optimize isolated multi-energy systems.

At this point of the thesis, a SWOT matrix is shown in order to highlight the drawbacks and the strengths, the threats and the opportunities of each tool. It is clear that there are some characteristics which usually go together in a tool: openness means also flexibility and programming ability, while closeness is related to user-friendliness and rigidity. Obviously, there are, as always, some exceptions. This does not mean that there are aspects in a model that are better than others, this only means that a user may choose the most appropriate tool on the basis of his need and objectives.

The overall results seem to underline the presence of two types of users with two different aims: the one that selects models with the end to promote the research field and the other one that prefers to choose tools for implementation, comparison, consultancy, or assessment. Therefore, the first kind of user looks for freely available and open energy models or frameworks because they are flexible and they allow to have lot of freedom in modifying the code, even if this also requires good programming abilities. In this way it is easy to adapt the energy system to developing countries conditions, which are always different and complex. On the contrary, the second one is more addressed towards easy to use and to understand tools, even if this could mean paying to download them and the inability to modify the code.

The tools included in the first group are Calliope, oemof, OSeMOSYS, URBS, ficus, Micro-Grids py and Multi energy system py. On the contrary, HOMER, iHOGA, INSEL and H2RES belong to the second one. Then, there are some models that are “in the middle” because they have characteristics belonging from both groups: for example, even if DER-CAM and poli.NRG are freely available, they are not also open; TOP-Energy is a commercial, user-friendly and closed software, characterized, however, by a lot of flexibility and freedom, for instance in the choice of technologies; LREM is freely available and open, but it is not suitable for modifying and adapting of the code, because it is has not the structure of a framework.

To conclude, it is possible to state that there is not the best multi-energy modelling tool, but the most suitable one, depending on specific user purposes and needs. Selecting the most appropriate model is crucial to obtain the right energy planning.

Despite HOMER has been considered for years by the literature the state of the art of the local energy system modelling, nowadays the attention is shifted towards new aims and towards the solution of new problems: the current global climate change, the decreasing of energy resources stocks, the decision to exploit renewable energy sources, the willingness to provide access to energy to all, the energy security aspiration, etc.

All this brings the research and the literature towards new energy system modelling tools, more flexible, transparent and fully accessible. For these reasons tools like Multi energy systems py, Calliope and oemof are starting to take hold, mainly due to the limitations of which HOMER is characterized and to the fact that it was created for the needs of another period.

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