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A new multiscale tool for simulating smart-grid energy management based on a systemic approach

Ando Ny Aina Randriantsoa[a], Damien Ali Hamada Fakra[b,*], Manitra Pierrot Ranjaranimaro[a], Mohamed Nasroudine Mohamed Rachadi[b], Jean Claude Gatina[b]

[a] *Higher Institute of Technology of Antananarivo (I.S.T), Ministry of Higher Education and Scientific Research, Iadiambola Ampasampito, Po Box 8122, Antananarivo 101, Madagascar*
[b] *Laboratory of Physics and Mathematical Engineering for Energy and the Environment (PIMENT) - University of La Réunion, 117 rue du General Ailleret - 97430 Le Tampon - La Réunion, France*

Abstract

Electricity needs are growing rapidly in developing countries. Some governments are encouraging the integration of renewable energy into the electrical grid to deal with the environmental issues, depletion issues, and pollution issues from current conventional power generation systems. Therefore, a reliable tool is needed to manage this energy mix. A tool based on two new different strategies is proposed for the management of smart grids. A comparison with the HOMER software was carried out to ensure the reliability of the proposed tool to simulate the management of this energy mix. Furthermore, this tool is capable of simulating the management of energy-mix flows from a building to a country. Users can visualize the simulated environment in a two-dimensional map and graphs of the energy mix management associated with this environment. This approach can serve as a decision-support tool, for instance, in the implementation of a new photovoltaic field or wind turbines.

Keywords: SMARTEN, energy management, energy-mix, smart grid, multiscale, simulation

*Corresponding author
Email address: fakra@univ-reunion.fr (Damien Ali Hamada Fakra)
URL: piment.univ-reunion.fr (Damien Ali Hamada Fakra)

1. Introduction

Most activities today depend on energy and include transport, industry, housing, agriculture, air conditioning, and health. The most developed countries exhibit higher energy consumption [1]. However, global energy production is still dominated by fossil energy sources [2], and the economy and the consumption of fossil energy of a country are still closely linked [3]. Thus, the use of renewable energy sources is encouraged to address the problems of depletion and pollution of fossil energy sources. Nevertheless, renewable energy technologies [photovoltaic (PV) systems, wind turbine systems, etc.] still have the problem of intermittency [4]. Thus, to fully satisfy energy needs, an energy mix system is needed. Nonrenewable energy sources and renewable energy sources are mixed to satisfy the load. This energy mix has to be managed to optimize its use, and the current electrical grid is going to transition to a smart grid.

Smart grids are defined in many ways in the literature [5]. A smart grid is an electricity network that can intelligently integrate the actions of all users connected to it. This grid aims to deliver sustainable, economic, and secure electricity supplies. The latest technologies, computer science, tools and techniques will be taken into consideration to insert a form of intelligence into the electrical network [6] to optimize the energy flows distribution and integrate renewable energy sources.

The protection of the smart grid and maintenance of the power quality are considerable challenges for the integration of renewable energy in a smart grid [7]. Some solutions were suggested in the literature, such as the use of the Stockwell transform method to identify islanding, outage of renewable energy source or other faults in the network [8]. In this study, the protection of the grid against outage and power quality will be mostly assumed by the integration of batteries in the circuit. The algorithms of the proposed tool will also allow this protection by different operating parameters. Beyond these challenges, the integration of renewable energy in the smart grid will generate benefits including :

- More efficient transmission of electricity
- Quicker restoration of electricity after power disturbances
- Reduced operations and management costs for utilities, and ultimately lower power costs for consumers
- Reduced peak demand, which will also help lower electricity rates
- Increased integration of large-scale renewable energy systems
- Better integration of customer-owner power generation systems including renewable energy systems
- Improved security

In this paper, a simulation tool called Smart Management AlgoRiThm of Electricity Network (SMARTEN) will be described to manage this smart grid environment. The energy from the

current electrical grid will be mixed with renewable energy and energy from a storage system to fulfil the energy demands of the connected buildings.

The major contribution of this work is to propose two new strategies based on scenarios for simulating the management of energy flow in a smart grid. The algorithms of these strategies take into consideration the status of energy demand, renewable energy production, grid production, and storage batteries. The systemic approach used in this study has not been widely discussed in this field and can be considered a new and simple method to deal with energy flow management. The two-dimensional (2D) visualization proposed in this software is a tool that will help decision-makers observe every time step of the energy situation of each building in the connected grid.

This paper contains a bibliography of existing methods and tools; the operating principle of the new software, which includes a description of the two new algorithms based on scenarios; reliability tests of the software based on comparing validation elements with HOMER software; an example of an application that includes the input and output variables of the simulation and the parameters that the software needs to operate; and finally a general conclusion with ideas on how to improve the software.

2. State of the art

Optimization of the energy mix and management of the smart grid have been studied by several articles of research. In this section, state-of-the-art tools related to energy and energy-mix management will be described. The general uses of existing tools will be understood and the new tool developed in this study will be discussed.

2.1. Energy-mix optimization tools in buildings

There are studies focused on the relationship between the design of the building, energy mix associated with this building, and cost of energy (production and consumption). The most relevant papers in this field will be presented in the next several paragraphs. Fabrizio Ascione et al. [9] conducted research about the optimization of the energy mix in a building. In their paper, the developed optimization procedure was based on a genetic algorithm and was performed by the use of EnergyPlus and MATLAB software. Many tools allow simulations to optimize the energy and performance related to a building. A review of the optimization of building-energy tools was performed by Anh-TuanNguye et al. [10]; their paper shows that among these tools, the most used tool for building-energy simulation is EnergyPlus. Overall, 37.2% of major simulations about building optimization have been performed with this tool [10]. In this paper, compared with EnergyPlus, the proposed tool will be able to simulate energy flows from a single building to several buildings. The energy mix can be managed not only for a building but for an entire town or an island application.

2.2. Hybrid system designing tools

Before conceiving the new tool, a review of available hybrid system designing tools is needed. Many tools are available, so a comprehensive review is essential to understand their main features and choose the best types. Sinha and Chandel [11] presented a review of 19 software packages that help with the design, analysis, optimization, and economic viability of hybrid systems. A summary of these tools is shown in Table 1.

Table 1: Capabilities analysis of hybrid-system software tools [11]

Tools	Economical Analysis	Technical Analysis	PV System	Wind System	Generator set	Storage device	Bio-energy	Hydro energy	Thermal System
ARES-I &II	-	Yes	Yes	Yes	Yes	Yes	-	-	-
Dymola/Modelica	Yes	-	Yes	Yes		Yes			
HOMER	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
Hybrid Designer	Yes	-	Yes	Yes	Yes	Yes	-	-	-
HYBRID2	-	Yes	Yes	Yes	Yes	Yes	-	-	Yes
HYBRIDS	-	Yes	Yes	-	-	Yes	-	-	-
HybSim	Yes	Yes	Yes	-	Yes	Yes	-	-	-
HySim	Yes	Yes	Yes	-	Yes	Yes	-	-	-
HYSYS	-	Yes	Yes	Yes	Yes	Yes	-	-	-
iHOGA	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes	-
INSEL	-	Yes	Yes	Yes	Yes	Yes	-	-	Yes
IPSYS	-	Yes	Yes	Yes	Yes	Yes	-	Yes	-
RAPSIM	-	Yes	Yes	Yes	Yes	Yes	-	-	-
RETScreen	Yes	Yes	Yes	Yes	-	Yes	-	-	-
SOLSIM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	-
SOLSIM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	-
SOLSTOR	Yes	Yes	Yes	Yes	Yes	-	-	-	-
SOMES	Yes	Yes	Yes	Yes	-	Yes	-	-	-
TRNSYS	Yes	Yes	Yes	Yes	Yes	Yes	-	-	Yes
iGRHYSO	Yes	Yes	Yes	Yes	-	Yes	-	Yes	-

There are also authors who proposed a classification of these tools to allow for a specific orientation. Dave Turcotte et al. [12] proposed this classification: (1) Prefeasibility tools: mainly used to evaluate if there is global opportunity about implementing the system, this category of tool delivers a rough sizing analysis and often include a comprehensive cost and financial analysis (e.g., RETScreen); (2) Sizing tools: by performing a calculation of the system dimensions, users can insert an energy requirement, and the tool will determine the optimal size of each component related to the system; the energy flows among components and some indications about the critical periods of the year are provided by most of the sizing tools (e.g., HOMER); (3) Simulation tools: the user has to specify the nature and size of each component, and an analysis of the behavior of the system is then provided by the tool (e.g., HYBRID 2); (4) Open architecture research tools: traditional simulation tools do not allow users to modify the algorithms nor the behavior nor interactions of the individual components, while in an open architecture research tool, the modification of existing routines and the adding of new routines are allowed (e.g., TRNSYS). Researchers choose this tool category because of its flexibility and powerful application.

The time step of the simulation depends on the tool and the availability of input data (as weather data, for example), but simulations are commonly conducted on an hourly basis. Sizing operations can also be performed by simulation tools, but the user has to identify the key variables

of the system, then run the simulation, adjust the variable, and finally repeat the simulation until the system meets an acceptable sizing.

Luis Arribas et al. [13] proposed another classification method for hybrid system tools. In their report, four categories were listed : (1) Dimensioning: corresponds to the sizing tools of Dave Turcotte et al. [12] classification; (2) Simulation: corresponds to the simulation tools of Dave Turcotte et al. [12] classification; (3) Research: corresponds to the open-architecture research tools of Dave Turcotte et al. [12] and their classifications; (4) Minigrid design tools: assist in the design of a minigrid electrical distribution network.

The descriptions of these categories are the same as those of Dave Turcotte et al. [12] except for the minigrid design tools. This category allows users to determine if a stand-alone renewable energy home system or a system connected to the centralized system is more cost-effective for a single house in a village. Commonly, tools in the minigrid design category allow the users to minimize power losses in the distribution network at a proper voltage level and an adequate section of distribution cables [13].

2.3. Renewable-energy-integration tools

Connolly et al. [14] performed a survey of 37 computer tools regarding the integration of energy systems. In that survey, three hybrid simulation tools (HOMER, RETScreen, and TRNSYS) were reviewed. The survey was carried out with the collaboration of tool developers, and the following topics were studied: background information, users, tool properties, applications, case studies, and further information. Connolly et al. [14] proposed seven tool types that can be used to describe an energy tool. According to the authors, an energy tool can be associated with one or more types. These energy tool types are as follows:

- simulation tool, which simulates the operation of a system to supply the energy demand
- scenario tool, which usually combines a series of years into a long-term scenario
- equilibrium tool, which seeks to explain the behavior of supply, demand, and prices within a general or partial economy
- top-down tool, which uses general macroeconomic data to determine how energy prices and demands grow
- bottom-up tool, which identifies and analyzes specific energy technologies, investment options, and alternatives
- operation optimization tool, which optimizes the operation of a system; operation optimization tools are typically simulation tools
- investment optimization tool, which optimizes the investments in an energy system; investment optimization tools are typically scenario tools

The table 2 shows a summary of the 37 reviewed tools and indicates the type of each tool according to the classification of Connolly et al. [14].

Table 2: Type of each renewable-energy-integration tool reviewed [14]

Tool	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimization	Investment optimization
AEOLIUS	Yes	-	-	-	Yes	-	-
BALMOREL	Yes	Yes	Partial	-	Yes	Yes	Yes
BCHP Screening Tool	Yes	-	-	-	Yes	Yes	-
COMPOSE	-	-	-	-	Yes	Yes	Yes
E4cast	-	Yes	Yes	-	Yes	-	Yes
EMCAS	Yes	Yes	-	-	Yes	-	Yes
EMINENT	-	Yes	-	-	Yes	-	-
EMPS	-	-	-	-	-	Yes	-
EnergyPLAN	Yes	Yes	-	-	Yes	Yes	Yes
energyPRO	Yes	Yes	-	-	-	Yes	Yes
ENPEP-BALANCE	-	Yes	Yes	Yes	-	-	-
GTMax	Yes	-	-	-	-	Yes	-
H2RES	Yes	Yes	-	-	Yes	Yes	-
HOMER	Yes	-	-	-	Yes	Yes	Yes
HYDROGEMS	-	Yes	-	-	-	-	-
IKARUS	-	Yes	-	-	Yes	-	Yes
INFORSE	-	Yes	-	-	-	-	-
Invert	Yes	Yes	-	-	Yes	-	Yes
LEAP	Yes	Yes	-	Yes	Yes	-	-
MARKAL/TIMES	-	Yes	Yes	Partly	Yes	-	Yes
Mesap PlaNet	-	Yes	-	-	Yes	-	-
MESSAGE	-	Yes	Partial	-	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	-	-
NEMS	-	Yes	Yes	-	-	-	-
ORCED	Yes	Yes	Yes	-	Yes	Yes	Yes
PERSEUS	-	Yes	Yes	-	Yes	-	Yes
PRIMES	-	-	Yes	-	-	-	-
ProdRisk	Yes	-	-	-	-	Yes	Yes
RAMSES	Yes	-	-	-	Yes	Yes	-
RETScreen	-	Yes	-	-	Yes	-	Yes
SimREN	-	-	-	-	-	-	-
SIVAEL	-	-	-	-	-	-	-
STREAM	Yes	-	-	-	-	-	-
TRNSYS16	Yes	Yes	-	-	Yes	Yes	Yes
UniSyD3.0	-	Yes	Yes	-	Yes	-	-
WASP	Yes	-	-	-	-	-	Yes
WILMAR Planning Tool	Yes	-	-	-	-	Yes	-

On the other hand, there is no energy tool that can address all issues about the integration of renewable energy into the current electrical grid. Consequently, the choice of tool depends on the specific objectives of the final user. This indicates the importance of a review of existing tools about hybrid systems and renewable energy integration.

Sinha and Chandel [11] reported in a review of 19 tools of hybrid renewable energy systems that "HOMER is found to be most widely used tool as it has maximum combination of renewable energy systems and performs optimization and sensitivity analysis which makes it easier and faster

to evaluate the many possible system configurations." Through HOMER, Rajbongshi et al. [15] conducted an optimization of hybrid systems applied to rural electrification. HOMER has over 200,000 users around the world and is the global standard tool for microgrid and distributed energy system design [16], [17], [18]. In this study, a validation of SMARTEN will be conducted via a comparison of the results with HOMER.

3. Operating principle of SMARTEN

3.1. Hypothesis of simulation

Concept of SMARTEN is based on interconnected systems as shown in Figure 1. The upper

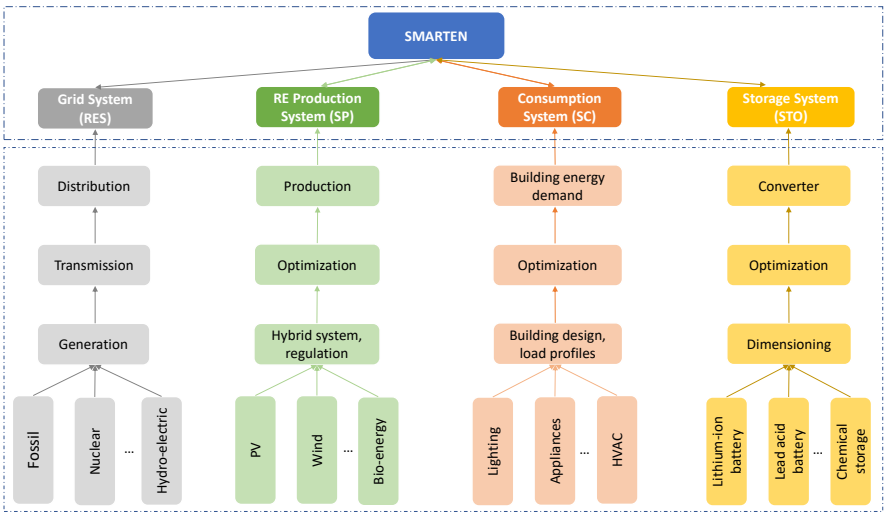

Figure 1: Relation between systems and SMARTEN

section is considered by SMARTEN, while the lower section consists of all subsystems related to the upper section and is not considered by SMARTEN.

The grid system (RES) used in SMARTEN does not include the process by which the electrical power is made available. There are several energy sources to feed the grid, and each country has its specific energy sources for that purpose. Chen and Wu [1] performed an overview of sources of energy around the world. To run a simulation in SMARTEN, the grid system is represented by the energy delivered by the grid that is available for the end customers.

For a renewable energy production system (SP), the energy sources can be from hydropower, solar energy (PV, thermal), biomass, wind energy, geothermal energy, or any renewable energy source. The renewable energy sources among the world and their uses were reported by REN21 [19]. In this study, each building could provide renewable energy from any hybrid system. Each building considered in the simulation was also connected to the grid. Therefore, to run a simulation in SMARTEN, the RE (Renewable Energy) production system was represented by the renewable energy available generated by each building.

Each building simulated in SMARTEN also has an energy demand (SC). Our tool takes into account 4 types of consumption profile: residential, industrial, community, and commercial. Thus, to run a simulation in SMARTEN, the consumption system is represented by the electrical power need for each building for each hour.

The storage system (STO) includes technologies and transformations for storing electrical energy. Research studies have been conducted in order to optimize and integrate storage systems into the grid [20], [21]. Palizban et al. also described the characteristics of energy storage applied in modern grids [22]. Thus, to run a simulation in SMARTEN, the storage system is represented by the energy available from the storage system (extraction process) and attributed to the storage system (charging process). As parameters, the higher and lower limits of the storage system are also considered. The converting process is taken into consideration in one of the two strategies in SMARTEN. In the development of our tool, we started with a battery storage model and intend to integrate other types of energy storage models.

3.2. Algorithms of strategy 1 description

SMARTEN has two control strategies depending on the final objective of the user. Strategy 1 aims to minimize consumption peaks and smooth the energy consumption curve. Strategy 2 aims to maximize the use of renewable energy and preserve environment.

SMARTEN is built under an algorithmic logic made up of different scenarios. Input data are modeled in a matrix format, and the calculation process of SMARTEN was developed in the MATLAB environment. This MATLAB environment is more efficient and widely used for matrix calculation. Therefore, the input data are represented by a $m \times n$ matrix where m are the rows that represent the time step (an hour) of the simulation, and n are columns that represent the buildings connected to the considered environment.

The management of energy distribution in a built space consists of knowing the situation of the different systems for each hour. SMARTEN can work on an hourly basis and interacts with four distinct systems [see Figure 2].

The main objective of strategy 1 is to minimize consumption peaks and smooth the energy consumption curve. For this purpose, when the consumption is close to a defined limit, energy is extracted from storage systems to avoid excessive extraction from the grid. Thus, priority is given to storage systems charging, and strategy 1 saves energy costs from the grid extraction. Table 3 shows data related to strategy 1.

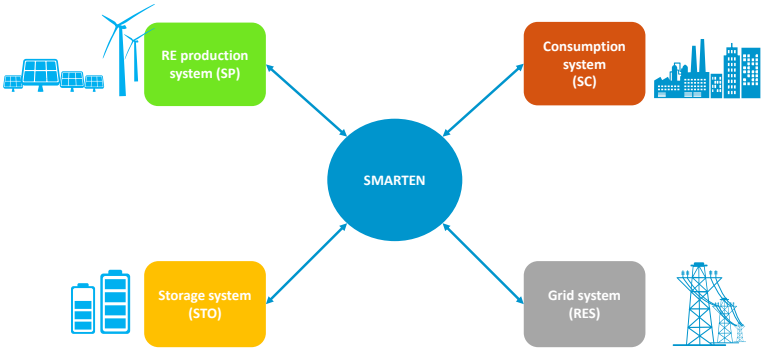

Figure 2: Relations between systems

Table 3: List of data needed in strategy 1

Input data	SP	renewable energy production system
	SC	consumption system
Parameters	LR	grid withdrawal limit
	LH	upper limit of storage capacity
	LB	lower limit of the storage capacity
	STOi-1	storage situation for the previous time step
Output data	RES	grid system extraction
	STO	storage system extraction
	EXC	excess energy production

The algorithm of strategy 1 deals with the production system and the consumption system to decide how the energy should be extracted from the electrical network or from the storage system and verify if there is any excess energy production. There are two main scenario cases:

- Case 1: The demand is less than or equal to the withdrawal limit at the network level
- Case 2: The demand is higher than the withdrawal limit at the network level

These two main cases can be split into several subcases in order to refine the management of energy flows. The simulation depends on the imported parameters. Figure 3 and 4 show a flowchart of strategy 1 and a flowchart of the calculation subroutine. These flowcharts determine how SMARTEN manages the energy flow according to each scenario.

If there is no RE production, then energy will be completely drawn from the grid. In strategy 1, there are 12 scenarios according to four parameters of numerical simulation. Energy demand will be met by the storage system until that storage system reaches the lower capacity limit. However, if the energy from the storage system is insufficient, then the rest will be drawn beyond the grid extraction limit from the grid system. If there is sufficient RE production to support the excess consumption not realized from the grid, then part of the energy demand can be ensured by this

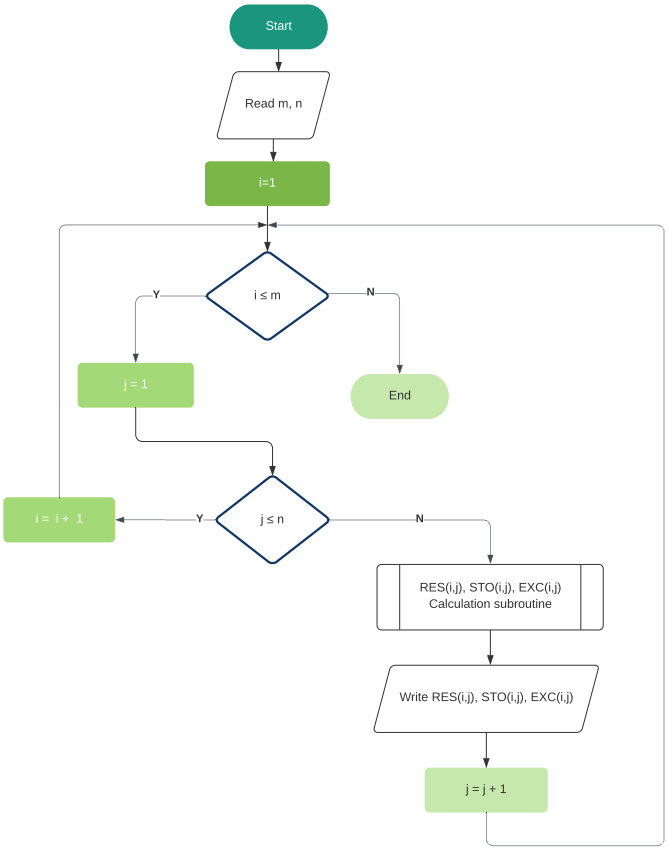

Figure 3: Flowchart of strategy 1

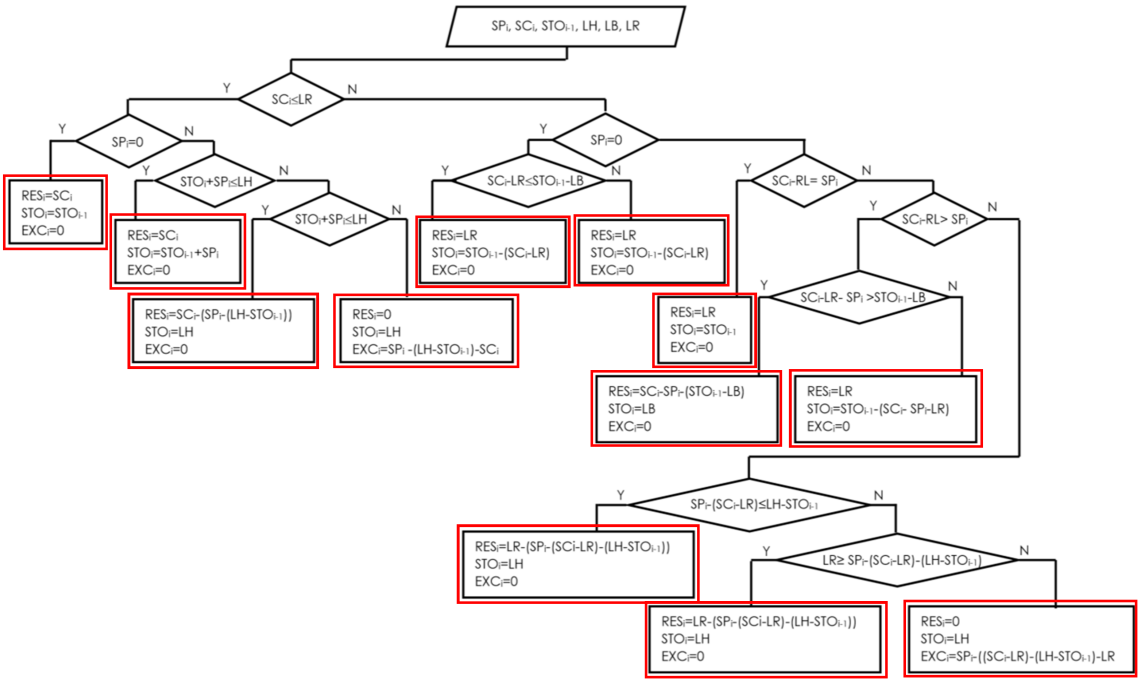

Figure 4: Flowchart of strategy 1 calculation subroutine

production. The consumption at the grid level becomes 0 when the production makes it possible at the same time to charge the storage system and to fully ensure consumption. There will even be excess energy in the best production condition.

3.3. Algorithm of strategy 2 description

Strategy 2 aims to control energy flows and maximize the use of renewable energy sources. Energy demand is first met by renewable energy sources when they are available, and therefore the storage system is only recharged when the energy demand is satisfied. Table 4 shows data related to strategy 2.

Table 4: List of data needed in strategy 2

Input data	SP	renewable energy production system
	SC	consumption system
	P_ch	battery maximum charging power
	P_dech	battery maximum discharging power
Parameters	rend_r	electrical grid efficiency
	rend_bat	storage battery efficiency
	rend_ond	converter efficiency
	ond_out_max	maximum output power of the converter
	ond_in_max	maximum input power of the converter
	LR	grid withdrawal limit
	LH	upper limit of storage capacity
	LB	lower limit of the storage capacity
	STOi-1	storage situation for the previous time step
Output data	RES	grid system extraction
	STO	storage system extraction
	EXC1	DC excess renewable-energy-production before the converter
	EXC2	AC excess renewable-energy-production after the converter

The algorithm of strategy 2 deals with the production system and the consumption system as strategy 1 does, but this algorithm also takes into account the battery maximum charging power and the battery maximum discharging power to decide how the energy should be extracted from the electrical network or from the storage system and verify if there is any excess energy production. The simulation depends on the same imported parameters as strategy 1, but there are five more parameters: electrical grid efficiency, storage battery efficiency, converter efficiency, maximum output power of the converter, and maximum input power of the converter. Figures 5, 6, 7, and 8 show a flowchart of strategy 2 and a flowchart of the calculation subroutine. These flowcharts determine how SMARTEN manages the energy flow according to each scenario.

The logic approach of strategy 2 is based on the RE production, and there are three main cases:

- Case 1: there is no RE production
- Case 2: the RE production can fulfill the energy demand

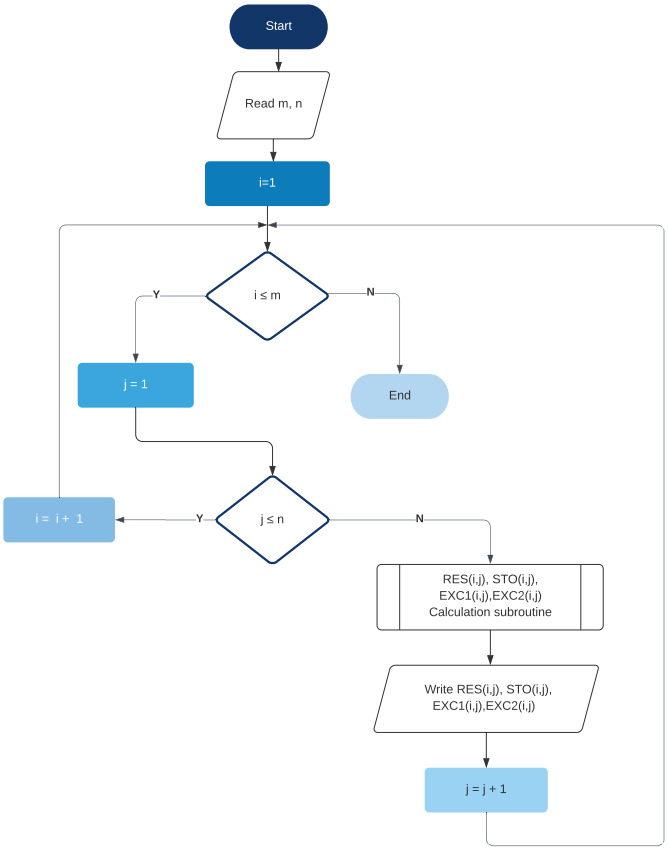

Figure 5: Flowchart of strategy 2

- Case 3: the RE production cannot fulfill the energy demand

If there is no RE production, then the algorithm checks if the energy consumption is less than the grid withdrawal limit. Thus, the demand is satisfied entirely by the electrical network. Beyond this limit, the rest of the energy demand is satisfied by the storage system. The extraction from this storage system depends on operating parameters of the converter and the storage device. The algorithm then extracts the energy from the storage system until its lower capacity limit is reached

If there is RE production, then the energy demand is fulfilled by the RE production, and the excess production will affect the charging storage device. This charging process continues until the higher capacity limit of the storage device is reached. If the consumption exceeds the converter maximum output power, then the rest of the energy demand is satisfied from the grid. If RE production is lower than the energy demand, then the algorithm extracts energy from the electrical grid. However, if the energy extracted from the grid exceeds the grid withdrawal limit, then the algorithm will verify the situation of the storage system.

To summarize, The management algorithm extracts first from the RE production, then from the electrical grid, and finally from the storage system. This storage system will only be charged if the energy demand is met. There are 20 scenarios according to strategy 2.

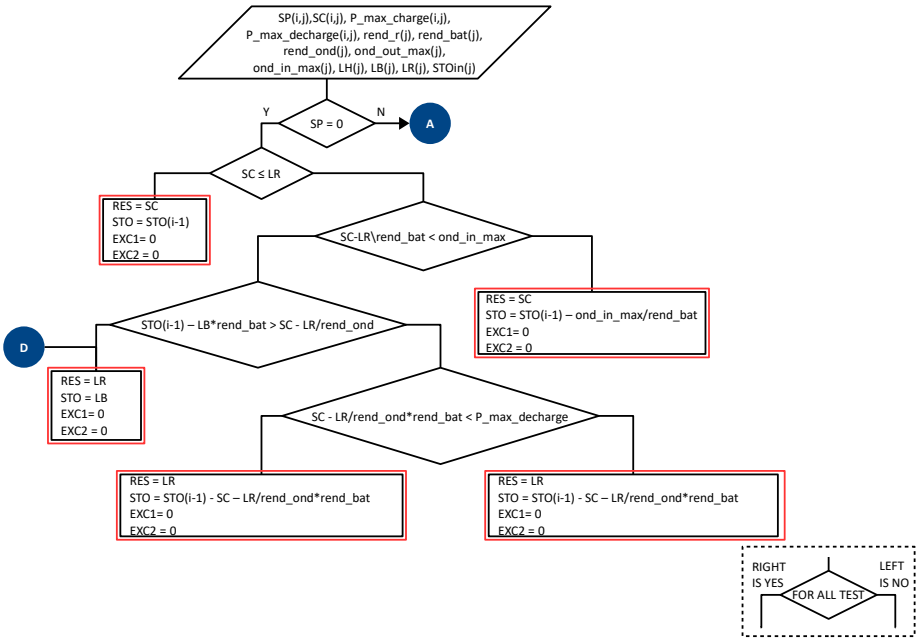

Figure 6: Flowchart of strategy 2 calculation subroutine - Part 1

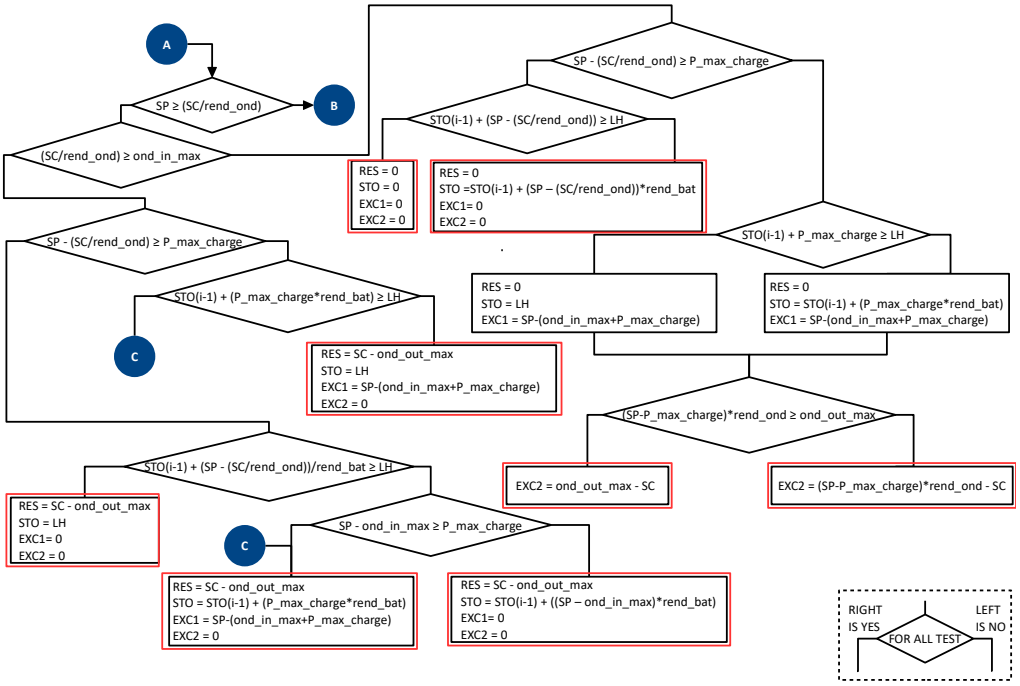

Figure 7: Flowchart of strategy 2 calculation subroutine - Part 2

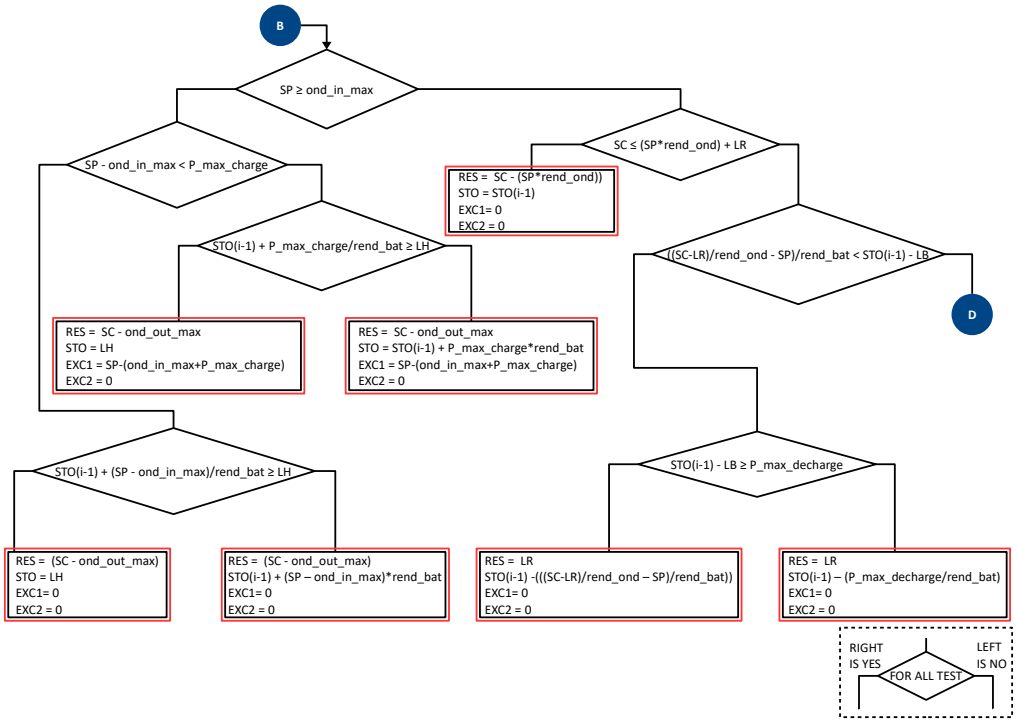

Figure 8: Flowchart of strategy 2 calculation subroutine - Part 3

4. Reliability tests: Comparison of energy-mix management between HOMER and SMARTEN

4.1. Hypothesis of comparison

To verify the reliability of SMARTEN, a validation by comparison with another tool is needed. The choice of the software to perform the comparison is based on what is commonly used in research and accepted by the research community.

Thus, HOMER PRO 3.11.5 software was selected to perform this comparison. HOMER (Hybrid Optimization of Multiple Energy Resources) was developed at the National Renewable Energy Laboratory (NREL/USA, United States of America) [16]. This software can be used for stand-alone systems or microgrid-connected systems. In addition, HOMER is a tool used to assist in the design, sizing, optimization, and simulation of hybrid renewable energy systems and is widely used by researchers to conduct simulations on new configurations of renewable energy systems [23], [24]. HOMER offers different configurations to users depending on their purpose. It can be used to identify the least expensive options. Among the features of HOMER is support of the hourly profile of the electrical consumption.

Two main strategies govern the optimal management of energy fluxes by the software. We have

- Following Load: the strategy consists of meeting demand by following the load at all times from the renewable energy source first, then from the grid if the renewable energy production

is not sufficient. In this strategy, batteries are charged only by photovoltaic energy production during low energy demand.

- Cycle Charging: the energy demand is met by the grid until a defined level of power. Beyond this level, the batteries supply the energy. The generator's (i.e., photovoltaic system) excess production is used to recharge the batteries first. If renewable energy is not available, then the batteries are recharged by the grid.

The mathematical modeling of HOMER is also described in Table 5 to allow for a better understanding of the selected software.

Table 5: Mathematical Modeling of HOMER [25]

HOMER Calculation	**Equation**
PV Array Output Power	$P_{PV} = Y_{PV} f_{PV} (\frac{\overline{G_T}}{G_{T,STC}})[1 + \alpha_P (T_c - T_{c,STC})]$
Hydro Power Output	$P_{hyd} = \frac{\eta_{hyd} \cdot \rho_{water} \cdot g . h_{net} . Q_{turbine}}{1000 W/kW}$
Clearness Index	$K_T = \frac{H_{ave}}{H_{o,ave}}$
Maximum Battery Charge Power	$P_{batt,cmax,kbm} = \frac{kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{1-e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})}$
Maximum Battery Discharge Power	$P_{batt,dmax,kbm} = \frac{-kcQ_{max} e^{-k\Delta t} + kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{1-e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})}$
Wind Turbine Power Output	$P_{WTG} = (\frac{\rho}{\rho_0}).P_{WTG,STP}$

Where:

- Y_{PV} = rated capacity of the PV array, meaning its power output under standard test conditions [kW]
- f_{PV} = PV derating factor [%]
- $\overline{G_T}$ = solar radiation incident on the PV array in the current time step [$kW.m^{-2}$]
- $G_{T,STC}$ = incident radiation at standard test conditions [1 $kW.m^{-2}$]
- α_P = temperature coefficient of power [Â°C]
- T_c = PV cell temperature in the current time step [Â°C]
- $T_{c,STC}$ = PV cell temperature under standard test conditions [25Â°C]
- P_{hyd} = power output of the hydroturbine [kW]
- η_{hyd} = hydroturbine efficiency [%]
- ρ_{water} = density of water [1000 $kg.m^{-3}$]
- g = acceleration due to gravity [9.81 $m.s^{-2}$]
- h_{net} = effective head [m]

- $Q_{turbine}$ = hydroturbine flow rate $[m^3.s^{-1}]$
- H_{ave} = monthly average radiation on the horizontal surface of the earth $[kWh.m^{-2}.day^{-1}]$
- $H_{o,ave}$ = extraterrestrial horizontal radiation, meaning the radiation on a horizontal surface at the top of the earth's atmosphere $[kWh.m^{-2}.day^{-1}]$
- Q_1 = available energy [kWh] in storage at the beginning of the time step
- Q = total amount of energy [kWh] in storage at the beginning of the time step
- c = storage capacity ratio [unitless]
- k = storage rate constant $[h^{-1}]$
- Δt = length of the time step [h]
- Q_{max} = total capacity [kWh] of the storage bank
- P_{WTG} = wind turbine power output [kW]
- $P_{WTG,STP}$ = wind turbine power output at standard temperature and pressure [kW]
- ρ = actual air density $[kg.m^{-3}]$
- ρ_0 = air density at standard temperature and pressure (1.225 $kg.m^{-3}$)

In SMARTEN, a systemic approach is used to manage a smart grid. The behavior of the proposed tool depends on several conditions and parameters, and the production and consumption data are imported as .xlsx files. The calculation of power outputs of renewable energy sources is not included in SMARTEN. These data are imported from existing studies. The proposed tool does not take into consideration these subsystems of production as seen in Figure 1. The algorithms of the two strategies of SMARTEN focus only on the management of the energy flow. The energy flow management of the proposed software is shown in Figure 9.

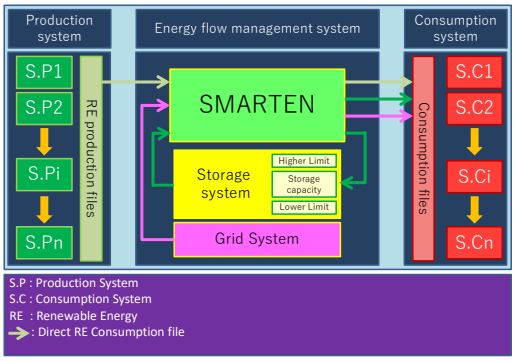

Figure 9: Energy flow management system

For the reliability test, we loaded in SMARTEN and HOMER with the same data related to four buildings: three residential buildings and one commercial building. The Production System (SP) used for the simulation is a solar energy production by photovoltaic panels. The storage system used for the simulation consists of batteries. Production of renewable energy is provided by the National Aeronautics and Space Administration (NASA) annual database in Colorado, United

States, from January 1 at 00:00 to December 31, 2007, at 23:00 corresponding to 8760 hours of simulation.

The parameters of the simulation are given in Table 6, and the grid system efficiency is supposed to be 0.80. The parameters are as follows: ηbat refers to the storage battery efficiency, $\eta conv$ refers to the converter efficiency, Max conv. is the output for the maximum output power of the converter, Max conv. is the input for the maximum input power of the converter, LR is the grid withdrawal limit, LH is the upper limit of storage capacity, LB is the lower limit of the storage capacity, and STOi-1 is the storage situation for the previous time step. The values of the efficiency of the batteries and converter are needed for the comparison, and the Following Load strategy of HOMER is closer to strategy 2 of SMARTEN. Thus, strategy 2 of SMARTEN was used for this comparison.

Table 6: Parameters of simulation in SMARTEN

Building	ηbat	$\eta conv$	**Max conv. output (kW)**	**Max conv. input (kW)**	**LR (kWh)**	**LH (kWh)**	**LB (kWh)**	**STOi-1 (kWh)**
Residential 1	0.89	0.95	1.22	1.29	1.50	5.00	2.00	5.00
Residential 2	0.89	0.95	0.48	0.51	1.50	2.00	0.80	2.00
Commercial	0.89	0.95	137.72	144.97	255.00	379.30	151.72	379.30
Residential 4	0.89	0.95	2.59	2.72	1.50	11.01	4.40	11.01

4.2. Results of the reliability test

An advantage of SMARTEN compared to HOMER is that the simulation for all four buildings is made simultaneously, while on HOMER, the simulation is carried out building by building. This is the multiscale aspect of SMARTEN. Thus, this multiscale aspect allows the distribution of energy-mix flows into connected buildings of the simulated environment.

Figure 10 shows the variation of the storage system for a year of simulation for Residential Building 1. On the second y-axis, it shows the relative error between SMARTEN and HOMER for that variation.

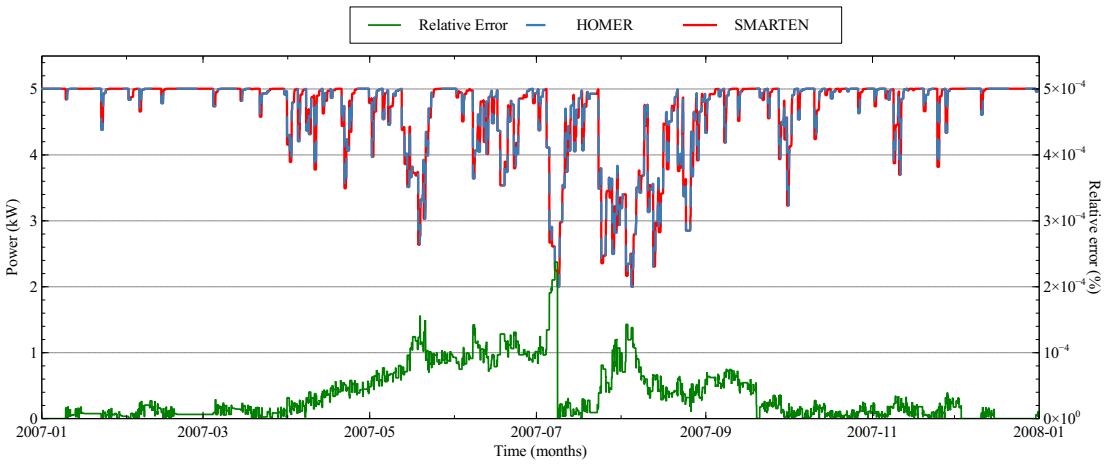

Figure 10: Storage system variation and relative error for Residential Building 1

As seen in Figure 10, where the maximum relative error about storage system is found during the entire simulation, the difference between SMARTEN and HOMER is very close. The maximum relative error is observed on July 7, 2007, at 19:00. It corresponds to a difference of power approximately 5.34 W, which refers to a 2.4x10^{-4}% relative error. This result is due to higher energy demand met by the storage system and emphasizes the slight difference between the two tools.

Figure 11 shows the variation of the grid extraction from January 1 at 00:00 to January 20, 2007, at 23:00 for the Commercial Building. The second y-axis shows the relative error between SMARTEN and HOMER for that variation. This range of time is chosen for Figure 11 to allow better visualization of the maximum error in the variation of the grid extraction.

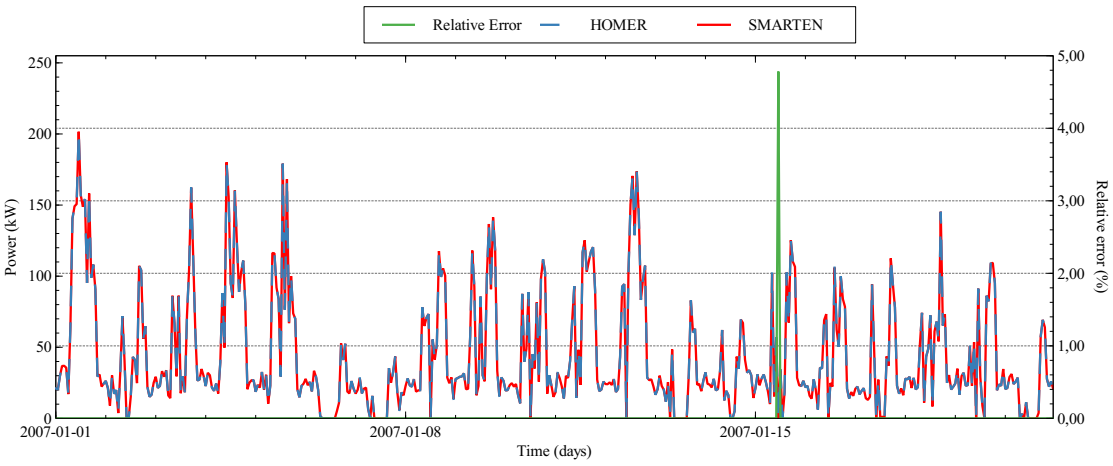

Figure 11: Grid extraction variation and relative error for Commercial Building

Figure 11 shows that general management simulation proposed in SMARTEN algorithms (particularly with strategy 2) is very similar to the management of the HOMER software. The maximum error between SMARTEN and HOMER corresponds to a difference of power of approximately 45.2 W. Thus, the maximum relative error value is 4.78%. For that Commercial Building, the grid withdrawal limit is approximately 255 kWh. As a result, the power difference compared to the grid withdrawal limit is negligible (1.77x10^{-2}%). The differences between residential and commercial buildings are the capacity of the storage system, the proprieties of the converter, and the grid withdrawal limit. These parameters contribute to a higher relative error for simulating commercial buildings compared to residential buildings.

Finally, the maximum error values for the simulations of these four buildings are summarized in Table 7. Very small errors of approximately 2x10^{-4}% are found for storage system management and errors not exceeding 5 % for grid extraction management. These comparison results indicate the reliability degree of SMARTEN to manage the energy mix in a smart grid environment.

Table 7: Relative errors committed by SMARTEN compared to HOMER software simulation for management of energy mix in a building

	Relative error (%)	
Buildings	Grid extraction	Storage system
Residential 1	4.73×10^{-2}	2.40×10^{-4}
Residential 2	1.39	1.50×10^{-4}
Commercial	4.78	1.60×10^{-4}
Residential 3	2.54×10^{-2}	8.00×10^{-5}

4.3. Conclusion of reliability tests

The SMARTEN reliability tests are essential for its implementation. The purpose of these reliability tests by comparison with the HOMER software is to check whether the results found in SMARTEN correspond to the results found in software widely used by researchers across the world under same hypothesis and parameters. During the simulation of the energy-mix management of four buildings, results obtained by SMARTEN differ from HOMER by approximately 2x10^{-4}% for power extracted from storage batteries and by approximately 4.78% for power withdrawn from the grid. This reliability test, by comparison, shows that results obtained by SMARTEN agree closely with those obtained by HOMER software both for storage system management and grid extraction management.

Comparison between HOMER and SMARTEN summarized in Table 8 according to classification method of Connelly et al. [14] with additional specifications related to this study.

Table 8: Comparison between SMARTEN and HOMER

	SMARTEN	HOMER
Simulation	Yes	Yes
Scenario	-	-
Equilibrium	-	-
Top-down	-	-
Bottom-up	-	Yes
Operation Optimization	Yes	Yes
Investment Optimization	-	Yes
Conception Method	Systemic Approach	Mathematical Modeling
Multiscale simulation	Yes	-
Multiscale 2D Visualization	Yes	-

The main difference between SMARTEN and HOMER is the conception method. SMARTEN uses a systemic approach while HOMER uses mathematical modeling. Another difference about running simulations is the multiscale aspect. Simulating several buildings is laborious in HOMER because each building is simulated one by one. In SMARTEN, the simulation of these four buildings is conducted simultaneously. Savings in time and labor is therefore observed when using

SMARTEN. Furthermore, the possibility of 2D visualization of all buildings simulated in a territory makes SMARTEN more efficient about time and space management. This aspect is detailed further in paragraph 5.3.2.

5. Example of application

5.1. Objective of application

After validating the reliability of SMARTEN in comparison to HOMER, an example of application is then presented in this section. The main objective of this example of application is to demonstrate the main features of the proposed tool in the management of energy flow. The proposed tool will be applied in a single building and then in a smart grid composed of 20 interconnected buildings to understand the impact of the 2D visualization in decision-making.

5.2. Hypothesis of application

The algorithms of strategy 1 and strategy 2 are inserted in a graphical user interface (GUI). The GUI was designed in a 64-bit version of Windows and the MATLAB 2015b release in order to allow for fluid calculation of larger matrices.

5.2.1. Hypothesis of single-building application

For this application of SMARTEN in a single building, the renewable energy source (PV) is a set of solar panels, and the storage system (STO) consists of batteries. The profile of production of renewable energy was provided by the NASA annual database in Colorado, USA, in 2007. Two dates were chosen to determine the impact of the use of SMARTEN: June 21 (see Figure 12), which corresponds to the summer solstice; and December 21 (see Figure 13), which corresponds to the winter solstice in the Northern Hemisphere. Strategy 1 of SMARTEN is selected to smooth the consumption and reduce the energy cost. The algorithms of this strategy will smooth the energy consumption by using storage units to supply the energy demand beyond a defined limit to avoid excessive costs of energy.

The grid system efficiency is supposed to be 0.80, and the other parameters used in this application are set by a typical commercial building load profile (see Table 9).

Table 9: Parameters of commercial building application

Building	ηbat	$\eta conv$	**Max conv. output (kW)**	**Max conv. input (kW)**	**LR (kWh)**	**LH (kWh)**	**LB (kWh)**	**STOi-1 (kWh)**
Commercial	0.89	0.95	137.72	144.97	255.00	379.30	151.72	379.30

5.2.2. Hypothesis of microgrid application

In this example of application in a smart grid, the renewable energy source (PV) is also considered a set of solar panels, and the storage system (STO) consists of batteries. The profile of production of renewable energy was provided by the NASA annual database in Colorado, USA, for January 1, 2007. For this application, strategy 2 of SMARTEN was selected to maximize the use of renewable energy to meet the energy demand extraction. The algorithms of this strategy will smooth the energy consumption by using the renewable energy sources and storage units to supply the energy demand. This management strategy will minimize the extraction from the grid.

As with the previous hypothesis, the grid system efficiency is supposed to be 0.80, and the other parameters used in this application are set by a random distribution of 20 residential buildings' typical load profiles.

5.3. Results of application and interpretation

5.3.1. Results of single-building application

For the single-building application, the results paragraph will focus on the impacts of SMARTEN in the management of energy mix and energy cost savings.

On June 21 (see Figure 12), the sun rose at around 6:00 a.m. The first part of the graphic shows that there is no renewable energy production between 12:00 a.m and 6:00 a.m. The energy demand was supplied by the grid, so the consumption and grid withdrawal curves are mixed. From 6:00 a.m to 18:00 p.m, the photovoltaic panels produced energy, and most of the energy demand was supplied by the renewable energy. Thus, the grid withdrawal curve was under the consumption curve due to renewable energy production. Beyond 18:00 p.m, there was no renewable energy production, and the energy demand was entirely supplied by the grid.

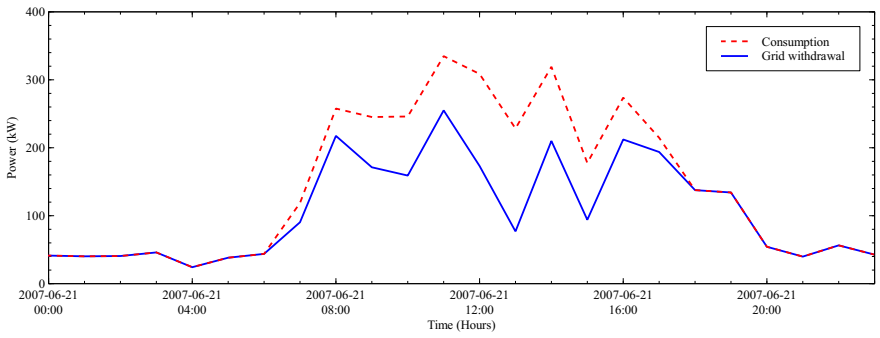

Figure 12: Impact of SMARTEN for commercial building consumption on June 21, 2007

A peak of consumption of 334.8 kW was detected at 11:00 a.m. The grid extraction when using SMARTEN is limited to 255 kW according to the parameter LR (grid withdrawal limit), and a 23.83% of energy costs were saved by the proposed tool. The maximum energy saved was realized at 13:00 p.m when the photovoltaic panels produced the highest energy. At this time, 66.30% of the energy costs were saved using SMARTEN.

On December 21 (see Figure 13), the sun rose at around 5:00 a.m. Consequently, there was no renewable energy production from 12:00 a.m to 5:00 a.m., and hence, the consumption and the grid withdrawal curves are mixed. A difference between the consumption and the grid withdrawal curves was observed at 5:00. The photovoltaic panels continued to produce energy until 18:00. After this time, the energy demand was entirely supplied by the grid.

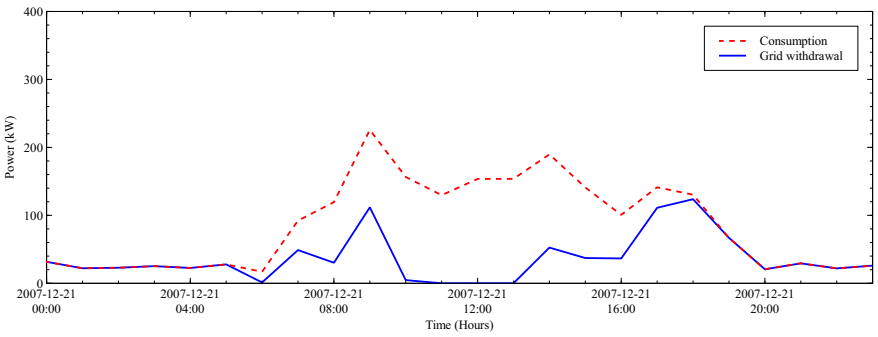

Figure 13: Impact of SMARTEN for commercial building consumption on December 21, 2007

The peak of consumption of approximately 225.73 kW was detected at 9:00 a.m, but only 111.79 kW was extracted from the grid, so 50.47% of the energy cost was saved by the use of the proposed software. On this day, when the renewable energy source production was optimum from 11:00 a.m to 13:00 a.m, the energy demand was entirely supplied by the renewable energy source. During this time gap, 100% of the energy cost could be saved by the use of SMARTEN.

The application of SMARTEN in a commercial building can allow users to save approximately 23.83% of the energy cost during higher peaks of consumption. Under certain conditions, and when the renewable energy source production is at its highest, 100% of the energy cost can be saved. The integration of SMARTEN in the smart grid will save on energy costs and reduce the use of fossil energy, which is the main energy source of the current grid.

5.3.2. Results of smart grid application

For a smart grid application, the results paragraph will focus on the interface of SMARTEN and the impact of its 2D visualization in the management of energy flow in a smart grid.

SMARTEN has a very user-friendly interface. The user proceeds with the parameterization of the simulation by following the indications on this interface, such as the choice of the desired strategy and the import of data. A graph (see Figure 14) is also available in the interface to allow users to see the evolution of all data through time for each building. The ID (Identity Document) number of the 20 interconnected buildings and the display time (in hours) are editable in the graphics panel (1). Thus, the user can display the energy curves of a specific building separately. A legend (2) indicates each plotted data item by color, and zooming can be performed with the scroll of a computer mouse. In this example, Residential Building 2 has a consumption peak at 07:00 p.m. The algorithms of SMARTEN detect that the consumption is higher than the Network

Withdrawal Limit (LR), and the excessive consumption is fulfilled by the storage batteries because there is no renewable energy production.

Figure 14: Graphic display of SMARTEN

The main advantage of SMARTEN is the possibility to have a 2D visualization of the built environment system, district, city, town, or country. For this purpose, a "2D view" button is available. It opens another window dedicated to 2D visualization. The 2D visualization was developed using the Mapping Toolbox of MATLAB 2015b. Figure 15 is a 2D visualization of the village where 20 buildings are connected to SMARTEN. The data displayed is the consumption system of the 20 buildings at 08:00 p.m. Users can see the situation of all buildings connected to SMARTEN and choose which data to display on the map. In addition, a color bar (2) indicates the power range shown on the map, and the display time can be switched with a slider bar (1).

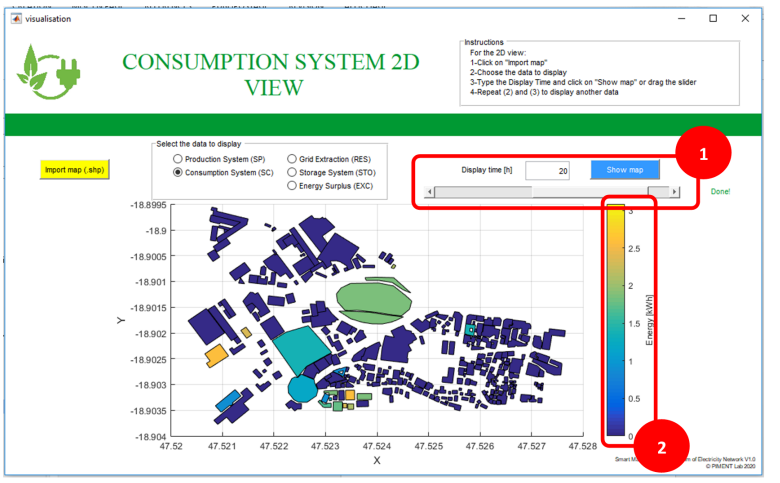

Figure 15: Two-dimensional visualization on SMARTEN

This possibility of 2D visualization is a very important asset for a decision support tool. Through this 2D visualization, it is possible to answer the following questions: which building has the most important energy consumption, which building has the maximum renewable energy

production, the location and time of the highest renewable demand, where to establish a new renewable energy system, and where to install the storage system. In this example, the residential building at the west side of the village has the highest consumption (yellow). Any questions about "where" and "when" related to the considered environment can be resolved by the use of the 2D visualization of SMARTEN. As a result, users can make a decision by taking into consideration the location of a specified building and the data related to it for every time step.

6. Conclusions and perspectives

The depletion and pollution issues of fossil energy sources and growth in global energy demand are the main reasons to use renewable energy sources. To compensate for the intermittency of these renewable energy sources, we use storage systems and mix them with the energy from the current grid system. A smart grid is thus implemented and has to be managed.

A new tool called Smart Management AlgoRiThm of Electricity Network (SMARTEN) was proposed. The software considers the renewable energy production and consumption systems to decide how the energy is extracted from the current electrical grid, from renewable energy sources, or from the storage system through different parameters. Two new strategies are available. Strategy 1 smoothes the consumption curve and avoids excessive energy costs, while strategy 2 maximizes the use of renewable energy and preserves the environment.

Reliability tests were conducted by comparison with HOMER software. For the storage system, a maximum relative error of approximately $2.4\text{x}10^{-4}\%$ was observed. For extraction from the electrical grid, a maximum relative error of approximately 4.78% was observed.

However, SMARTEN can simultaneously perform the simulation of several buildings when HOMER simulates only one at a time. In addition, SMARTEN can provide a 2D visualization of the area where the buildings are located. SMARTEN helps decision-makers determine the exact position of the future implementation of renewable energy systems: where to install new storage systems, renewable energy sources, the location and orientation of wind energy sources, the available space for a photovoltaic field, etc.

Further research to improve the software will be conducted by adding environmental and financial reports and new strategies. These are necessary to complete future releases of SMARTEN because it aims to be a decision-support and research tool.

Appendix A: Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix B: Acknowledgment

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Ando Ny Aina RANDRIANTSOA is an industrial engineer and currently a research intern at the PIMENT Laboratory of the University of La Reunion, France. He obtained a BSc degree in Automated System Engineering (2014) and an MSc degree in Industrial Engineering (2019) at the Higher Institute of Technology of Antananarivo, Madagascar. His research interests include energy harvesting and energy management.

Damien Ali Hamada FAKRA is a researcher at the SBE Department of the University of La Reunion, France. He obtained a Ph.D. in Buildings Science (2009) and his second Ph.D. in Energy Sciences (2020) at this university. Previously, he received an MSc degree in Mechanical and Energy Engineering at FST-MI University, Morocco. Since 2007, he has participated in 13 European funding projects.

Pierrot RANJARANIMARO is a researcher and senior lecturer at the Higher Institute of Technology of Antananarivo, Madagascar, where he is the Director of the Industrial Engineering School. He obtained a Ph.D. degree in Electronics and Industrial Computing from the University of La Reunion, France, and the University of Antsiranana, Madagascar (2019). Currently, his research interests include energy management and digital twins.

Mohamed Nasroudine MOHAMED RACHIDI is a teaching assistant for the SE3B degree at the University of Comoros. He obtained an MSc degree in Energy (2016) at the University of La Reunion, France. He was a research intern in the PIMENT laboratory at this University (2019). He also obtained an MSc degree in Energy Measurement (2018) at the University of Lorraine, France.

Jean-Claude GATINA joined the University of La Reunion, France, in 1979 and has been a professor since 1993. His main functions were as follows: Laboratory Director (1993-1998), Director of a University Common Service (1993-2001), University Site Director (2001-2008), VP CEVU (2005-2008), and Director of the Training Service (2016-2020). He has directed approximately 40 theses and published approximately 100 articles and papers since 1993.