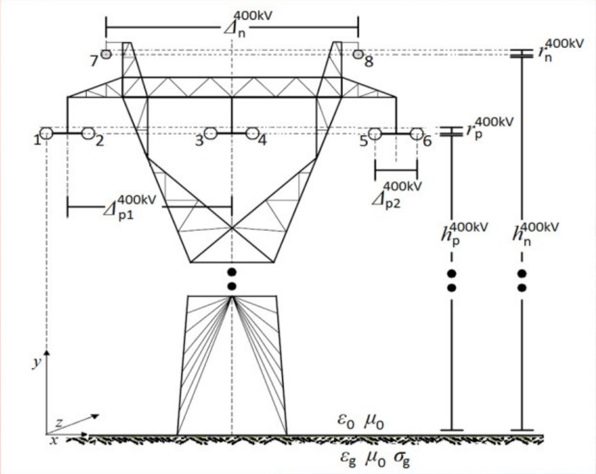
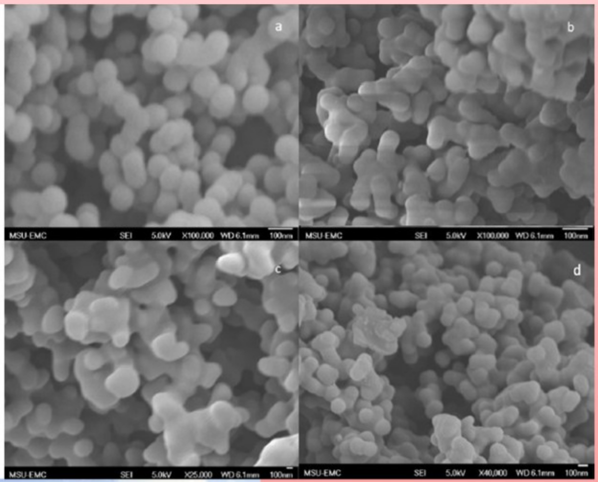
ISSN: 2376-2136 (Print)
ISSN: 2376-2144 (Online)

Trends in Renewable Energy

Volume 1, Issue 3, December 2015





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ISSN: 2376-2136 (Print) ISSN: 2376-2144 (Online)

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Trends in Renewable Energy, 2015, 1(3):129-197. DOI: 10.17737/tre.2015.1.3

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Trends in Renewable Energy
OPEN ACCESS ISSN: 2376-2144
EDITORIAL futureenergysp.com/index.php/tre

Recent Development of Bioenergy and Biorefinery in China

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Received September 6, 2015; Published September 10, 2015

Although energy was used throughout the history of human culture, the burst of energy production and consumption coincided with the beginnings of the Industrial Revolution. The transition from hand production methods to machines, as well as the increasing exploration and use of fossil-derived fuels (coal, petroleum, natural gas, and shale fuel) made it possible to produce energy in large quantities. The majority of global energy supply still relies on traditional fossil based energy, with abundant fossil feedstock, well-understood technologies, and significant advantages in economy and scale. However, the traditional energy industry is now being challenged by sustainability of feedstock supply and environmental pressures, especially for carbon emission issues. Reducing the use of fossil fuels and replacing them with renewable energies have been widely accepted by scientists, businesses, and governors. Up to date, alternative renewable energies can be industrially produced via an extensive range of processes and sources like solar, wind, hydro, nuclear, and bioenergy. According to the data of World Bioenergy Association (www.worldbioenergy.org), bioenergy has now been the largest global renewable energy supply, which is only lower than the traditional fossil energy.

China has abundant biomass resources that are about 0.4 billion tons per year - if totally utilized for generating bioenergy, it can satisfy 10% of total energy consumption in China. However, the current utilization of bioenergy in China is of low efficiency due to immature technologies, small-scale productions, and limited market channels. For example, in a global level, the final energy from biomass is bioheat, followed by transport fuels (mainly as corn/cellulose ethanol, biodiesel) and electricity. While in China, bioelectricity is the main form of bioenergy, large quantities of biomass are not efficiently utilized. Straw burning is still widely present in rural areas during the harvesting season, which not only wastes the valuable bioresources but also causes severe air pollution.

Currently, national projects are prompted in research and pilot levels to improve the quantity and quality of Chinese bioenergy framework. Integrated production processes for both bioheat and electricity were developed in recent years which aimed to improve the conversion efficiency of bioenergy. Super biogas projects are prompted in many regions where have abundant biomass resources. Second generation bio-ethanol achieved pilot-scale production, which is utilizing non-food agriculture wastes like the corncobs. Moreover, biorefinery and bioconversion of the biomass to value added products are in early stages of development. Exploration of advanced bio-fuels and value-added chemical building blocks using modern techniques are future trends in the business of bioenergy and biorefinery. A variety of bio-, chemo- processes may be integrated in

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Tr Ren Energy, 2015, Vol.1, No.3, 129-130. doi:10.17737/tre.2015.1.3.0015

conversion of the biomass to complex products. For example, Sinopec, one of the Chinese leading chemical companies, has explored 1st generation of bio-jet fuel, which is made from waste cooking oil via a variety of chemical processing techniques. Similar projects are in fast developing by industries as well as the research institutes.

It is hard to answer what is the future of bioenergy and biorefinery in China. As nobody in the last century can predict the scale and the diversity of the relative business of bioenergy in nowadays. But this industry will have a promising future: a seemingly infinite and renewable bio- resources in our lands, huge members of industries, governments and research institutes are eager to contribute their endeavors in this fast developing field, and more discoveries and modern techniques will be unfolded in the near future. We will walk a long way to fill in the gap between pioneering projects and conceptions and the practical scale-up application in this field.

Trends in Renewable Energy
OPEN ACCESS ISSN: 2376-2144
Peer-Reviewed Article futureenergysp.com/index.php/tre

Financially Stimulating Local Economies by Exploiting Communities' Microgrids: Power Trading and Hybrid Techno-Economic (HTE) Model

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Received July 26, 2015; Accepted September 5, 2015; Published September 10, 2015

This paper thoroughly considers the potential of installing microgrids (MGs) in communities that suffer from the economic crisis in order to financially stimulate their local economies. Exploiting the state-of-the-art evolutions in the fields of the MG technology, the Hybrid Techno-Economic (HTE) model is proposed as a suitable techno-economic tool for assessing the power generation/consumption behaviour and the financial performance of these communities' MGs.

The contribution of this paper is four-fold. First, the HTE model is presented. HTE model describes a theoretical analysis that is suitable for studying community's MGs. Appropriately concatenating one well-validated technical module and one new economic module, the HTE model quickly and conveniently reveals the power generation/consumption and economic profile of community's MGs. Second, HTE model is integrated through an extended portfolio of power and financial metrics. The applied metrics study the influence of generation and consumption power changes on community's MGs. The validity and the efficiency of the HTE model are examined with respect to these power changes while the impact of these changes on the power and cash flows of community's MGs are assessed. Third, a cost-benefit analysis of the operation of community's MGs accompanied with a financial stability analysis is also demonstrated. The main outcome of these analyses is the daily total benefit (TB) of community's MGs with its respective financial bounds. Fourth, the contribution of the energy arbitrage and the power production mix among available power sources of community's MGs to the daily TB is investigated.

Apart from promoting the ecological awareness, this paper tries to become a catching argument for the communities in order to exploit the community's MGs.

Keywords: Microgrids (MGs); Power Trading; Energy Arbitrage, Energy Storage Systems (ESSs); Distributed Generation (DG) sources; Renewable Energy Sources (RESs); Green Economy; Sustainable Development and Growth; Economy of Local Communities, Smart Grid

I. Introduction

The financial and economic crisis that started in the United States in 2007 and currently torments Europe has more or less impacted a vast majority of local

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Tr Ren Energy, 2015, Vol.1, No.3, 131-184. doi: 10.17737/tre.2015.1.3.0014

communities around the world. While the severity of these problems varies from one community to another, new policies have to be adopted as well as new tools and mechanisms have to be invented, restructured, and overhauled [1]-[4]. In a regional basis, the consequences of the financial and economic crisis mainly affects four sectors of community's economy [1], [5], [6]: (i) Revenues: The revenues of the communities, which are either generated by local taxation or derived from state transfers, have undergone dramatic declines; (ii) Expenditures: The communities suffering from the crisis show high unemployment and significant slowdown of their local economic activities. Hence, additional funding is required so that the general social welfare status is maintained; (iii) Bank financing: Apart from the states, the crisis critically affects the banking institutions as well as their cash liquidity. Hence, the cost of money increases while the communities face serious difficulties in contracting loans in order to satisfy their current budget needs and projections; (iv) Investments: The crisis environment discourages either foreign or local investors. This implies that various projects, which could create extra financial fluidity in local communities, are put on hold, cancelled or delayed. All the aforementioned reasons push local communities to immediately adopt measures that are going to enhance the community's sustainable development and to increase community's incomes.

Sustainable development and growth are an important issue for local communities that historically have been dependent on the exploitation of their natural resources (*i.e.*, forestry, agriculture, mining, and fishing) as their economic base [7]. Nowadays, by means of the prism of the green economy, communities can still commercialize their natural resources, such as wind speed and solar radiation, in order to financially stimulate their local economies [8]. This modern resource harvest can be achieved through microgrids (MGs) that are owned by the local communities [9]-[12]. Community's MGs are low-voltage power networks that include Energy Storage Systems (ESSs), Distributed Generation (DG) sources, like microturbines (MTs) and fuel cell (FC) units, Renewable Energy Sources (RESs), such as wind turbines and photovoltaic (PV) systems, and controllable loads [13]-[16]. In general, community's MGs operate interconnectedly to the main power grid, simply denoted as power grid [17]-[19]. However, community's MGs can operate isolatedly in case of external faults that block the interconnection with the power grid.

A community's MG can be considered as a controlled entity within the power grid that can be operated as a single aggregated load or as a small power source, which supports the operations of the power grid [20]-[24]. Apart from the satisfaction of its load consumption, a community's MG enhances local power reliability by regulating voltage and operation frequency, reduces greenhouse emissions and promotes ecological thinking through its RES operation, improves power quality and lowers energy supply costs [25]-[35]. Nevertheless, the interest of the communities suffering the crisis is also focused on the immediate revenues from the operation of their MGs by exploiting their energy arbitrage [36]-[46].

Energy arbitrage refers to earning a profit by charging the community's MG ESSs when energy market price is low and by selling their stored energy at higher energy market prices when the energy market price is high [30], [47]. The incomes from the energy arbitrage can further be increased through the careful power production mix among available ESS/DG/RES outputs of the community's MG [36], [40], [41], [48]. The units of community's MGs, which are going to produce energy, and their level of production are the result of an optimization procedure that aims at maximizing the daily total benefit (TB) of the community's MG [49]-[51]. However, it should be noted that the demand for electricity tends to be decreased during periods of economic crisis resulting in lower energy prices. Therefore, it is evident that the arbitrage opportunities cannot be considered as the main motivation to invest in community's MGs.

The optimization procedure of maximizing the daily TB of the community's MGs is included into the proposed Hybrid Techno-Economic (HTE) model. Actually, the HTE model consists of two modules, namely: (i) *the technical module*. It defines the optimal power mix among available ESS/DG/RES outputs of the community's MG and the energy trade with the power grid in a long-term horizon. The technical module incorporates the simplicity of Mixed Linear Integer Problem / A Modeling Language for Mathematical Programming (MLIP/AMPL) method presented and verified in [52]; and (ii) *the economic module*. Due to its simplicity, this module permits its continuous (e.g., hourly) application without the need of specialized personnel or special software. The economic module is used complementarily to the technical module and provides very short-term decision adjustments.

On the basis of a plethora of simulation results as these are derived from the HTE model, several interesting findings concerning the operation and financial performance of community's MGs are demonstrated in this paper. The detailed power profile and the analytical cash flows related to the community's MG operation are extensively assessed. Except for the results concerning the baseline scenario, which have already been validated in [52] and used in this paper, the financial stability of the community's MG is investigated when different power production and consumption scenarios occur. In addition, using an extended portfolio of suitable power and financial metrics, that is supported by the HTE model, the exact power and financial impact of the operation of each component of the community's MG is evaluated as well as the power and financial reaction of the community's MG when power changes occur. Finally, the applicability, validity, and practicability of the economic module are highlighted for different power production and consumption scenarios that may occur when different policies concerning the power allocation among available power sources, which are dictated by the economic module, are adopted.

The rest of this paper is organized as follows: In Section II, a synoptic cost-benefit analysis of the community's MG case is presented. Attention is given on the energy arbitrage. Section III provides the analytical framework concerning the operation of the HTE model (*i.e.*, its modules and its objectives). In Section IV and V, a thorough presentation of the technical module and the economic module of the HTE model is outlined, respectively. In Section VI, extended numerical results and discussion identify and assess the power and financial performance of community's MGs and their mitigating role against the crisis consequences. Section VII includes background to ideas for future work. Section VIII concludes this paper.

II. Economic Analysis of Community's MGs

MG is no longer a novel idea. Rather, it is an academic and commercial venture that needs time to prove its financial value. As the industry matures, MGs steadily move from a curiosity to the reality [53].

In fact, the initial economic analyses of MGs have mainly focused on peak shaving and capacity resource applications [41], [54]. Recently, there has been some attention given to applying MG operation as a backup for intermittent RESs [38], [41],

[44], [54]-[56]. In recent years, with the emergence of competitive energy markets, several economic studies of MGs have appeared, covering a broader range of applications [36], [45], [46], [57]-[61]. Among these studies, one very interesting application highlights the role of MGs in order to achieve 'small device' energy arbitrage under the assumption that MGs are small enough –*i.e.*, their charge and discharge operations do not affect the overall market price of energy–. Actually, this economic operation is mainly achieved through the ESSs of MGs; ESSs absorb low-priced energy and then discharge it during higher-priced hours [36], [49], [52].

To increase revenues from energy arbitrages, communities' MGs try to replace their more expensive DG operation during peak load periods with less expensive types of energy. These expensive types of energy can be either stored in their ESS or directly delivered from the power grid. Community's MGs may consist of different DGs and ESSs rendering the problem of optimal DG/ESS outputs, and thus the issue of TB maximization is significantly complicated; in most of the cases, the solution comes from a mixed-integer linear problem. Recently, a series of methods has been proposed in order to accurately determine the optimal mix among available ESS/DG/RES outputs and the energy market [9], [17], [19], [32], [49], [52], [62], [63].

Nevertheless, on the basis of the small communities that decide to deploy MGs as an additional revenue to their budgets, the 24-hour technical support of this sophisticated equipment requires extra resources such as the cost of the specialized personnel that deals with the community's MG issues and the relative decisions concerning its operation. To reduce these communities' expenses and make the idea of community's MGs more tempting, the HTE model can be used. In fact, HTE model comprises a concatenation of one technical and one economic module.

III. HTE Model and its Modules

Actually, the HTE model, which is proposed in this paper, consists of two modules, namely:

- *Technical module*. Based on historical weather data and long-term forecasts, the technical module is applied in order to define the optimal energy mix among available ESS/DG/RES outputs and the energy market in a long-term horizon. The proposed technical module incorporates the optimization procedure of MLIP/AMPL method presented in [52]. In Section IV, the technical module is analytically presented.
- *Economic module*. As it concerns the short-term decision adjustments, this module could be used so that essential decisions are taken in order to compensate inevitable discrepancies that arise due to either divergences between historical and real-time conditions or equipment malfunctions. The simplicity of this module permits its continuous application without the need of specialized personnel or special software. In Section V, the economic module is detailed.

Therefore, the technical module of [52] gives a long-term solution while the economic module can provide short-term decision adjustments. Although the technical module presented in [52] has an hourly resolution and an optimization horizon of about 24 hours, the technical module, used in HTE model, is applied in order to provide long-term predictions based on historical data and long-term forecasts.

The goal of the HTE model is not only to provide an optimal mix solution among ESS/DG/RES outputs and energy market but to offer a quick and convenient model for small communities that decide to install MGs so as to create additional revenues in order to financially stimulate their local economies. More specifically, in techno-economic terms, the objective of the HTE model is for given power change *p*% in the daily MG production or load consumption (see also Section V), the community can still satisfy its daily power needs while its daily TB change is maintained lower than *p*%. Actually, the HTE model tries to implement an economic stable system where the TB of the economic module is near to the TB of the baseline scenario that is defined by the technical module (optimal solution and equilibrium point) [64].

IV. Technical Module

In accordance with [49], [52], to properly tune the technical module in a long-term prediction mode, a number of key input parameters related with the operation of community's MG is required. In fact, there are two sets of parameters, which are detailed in the following analysis, that are initiated in the technical module, namely:

- *Power-related input parameters*. These parameters are related to the power production and power consumption characteristics of the community's MG.
- *Finance-related input parameters*. These parameters have to do with the operational cost and operational benefit of the community's MG.

Similarly to its inputs, the technical module delivers two sets of outputs that correspond to the optimal mix among available ESS/DG/RES outputs and power grid:

- *Power-related output parameters*. These parameters are: (i) Optimal power and energy production/storage of ESS; (ii) Optimal power production of DGs; (iii) Power production of RESs; and (iv) Optimal energy trade with the power grid.
- *Finance-related output parameters*. These parameters provide the base of the cost/benefit analysis and are synopsized by the metrics: (i) Daily cost of ESS; (ii) Daily cost of DGs; (iii) Daily cost of RESs; (iv) Daily Market Benefit (MB); and (v) Daily TB. The finance-related output parameters are also used by the economic module.

On the basis of the maximization of the daily TB, the outputs of the technical module are defined through the prism of energy arbitrage and of certain technical constraints regarding the operation of community's MGs [52].

A. Daily Cost of ESS

ESS of community's MGs that is examined in this paper consists of battery energy storage systems (BESSs). These BESSs are made up of small battery blocks in series and in parallel connections. Prior to determine the daily cost of ESS $C_{\mathrm{daily}}^{\mathrm{ESS}}$, there is a need of evaluating two other related daily sub-costs, namely:

- *Daily Capital Cost of ESS* $C_{\mathrm{daily,capital}}^{\mathrm{ESS}}$: Capital cost of ESS $C_{\mathrm{capital}}^{\mathrm{ESS}}$ is a fixed, one-time expense realized during the purchase of ESS. It is the total cost needed so as to bring ESS of community's MG to its first commercially operable status (*e.g.*, purchase cost, installation cost, etc). In this paper, as the relevant costs and gains are calculated in 24h, which is one day, the capital cost of ESS is normalized on a daily basis, namely:

$$C_{\text{daily,capital}}^{\text{ESS}} = \frac{1}{365} \cdot CRF(r,l) \cdot \underbrace{\left[S_{\text{kW}}^{\text{BESS}} \cdot C_{\text{purchase, kW}}^{\text{BESS}} + S_{\text{kWh}}^{\text{BESS}} \cdot C_{\text{purchase, kWh}}^{\text{BESS}}\right]}_{C_{\text{capital}}^{\text{ESS}}} \tag{1}$$

where

$$CRF(r,l) = \frac{r(1+r)^l}{(1+r)^l - 1} \tag{2}$$

is the capital recovery factor that is used in order to normalize the capital cost of ESS in present values, r is the interest rate, $S_{\text{kW}}^{\text{BESS}}$ is the power capacity of BESS in kW, $S_{\text{kWh}}^{\text{BESS}}$ is the energy capacity of BESS in kWh, $C_{\text{purchase, kW}}^{\text{BESS}}$ is the purchase cost of BESS in \$/kW and $C_{\text{purchase, kWh}}^{\text{BESS}}$ is the purchase cost of BESS in \$/kWh where \$ is the US dollar currency. Note that the ESS repayment period is assumed equal to l years. From eq. (1), it is evident that the capital cost of ESS depends on the power capacity –*i.e.*, storable energy– and energy capacity –*i.e.*, peak power that the storage must deliver– of its BESSs; say the capital cost is proportional to the size of its BESSs [49].

- *Daily Maintenance Cost of ESS* $C_{\text{daily, maintenance}}^{\text{ESS}}$: The maintenance cost of ESS $C_{\text{maintenance}}^{\text{ESS}}$ is the annual maintenance cost of ESS. Similar to the capital cost, the maintenance cost is proportional to the size of BESS and is given by

$$C_{\text{daily,maintenance}}^{\text{ESS}} = \frac{1}{365} \cdot \underbrace{S_{\text{kWh}}^{\text{BESS}} \cdot C_{\text{maintenance,kWh}}^{\text{BESS}}}_{C_{\text{maintenance}}^{\text{ESS}}} \tag{3}$$

where $C_{\text{maintenance,kWh}}^{\text{BESS}}$ is the maintenance cost of BESS in \$/(kWh·year). The maintenance cost is a variable cost.

With reference to eqs (1) and (3), the ESS daily cost of community's MG is defined by the sum of the above two daily costs:

$$C_{\text{daily}}^{\text{ESS}} = C_{\text{daily,capital}}^{\text{ESS}} + C_{\text{daily,maintenance}}^{\text{ESS}} \tag{4}$$

B. Daily Cost of DGs

DGs of community's MG that are examined in this paper consist of MTs and FC units. DGs are small single-staged combustion turbines while their power generation varies from few kWs to few MWs. DGs can be powered by diesel, natural gas or hydrogen [52]. Also, more than one DG is usually deployed in a community's MG. Similarly to the daily cost of ESS, prior to determine the daily cost of DGs $C_{\text{daily}}^{\text{DGs}}$, there is a need of evaluating three other relevant daily sub-costs, namely:

- *Daily Capital Cost of DGs* $C_{\text{daily,capital}}^{\text{DGs}}$: It depends on the size of DGs of community's MG and their operating hours. In fact, the daily capital cost of each DG $C_{\text{daily,capital}}^{\text{DG},i}$ of community's MG includes its DG purchase cost, DG installation cost, DG maintenance cost and DG fuel cost. Similarly to eq. (1) and in accordance with [52], [65], the daily capital cost of DGs is determined from

$$C^{\mathrm{DGs}}_{\mathrm{daily,capital}} = \sum_{i=1}^{noDG} \left\{ \underbrace{\left[\sum_{t=1}^{24} U_t^{\mathrm{DG},i} \cdot \left(C^{\mathrm{DG},i,1} + P_{\mathrm{t}}^{\mathrm{DG},i} \cdot C^{\mathrm{DG},i,2} \right) \right]}_{C^{\mathrm{DG},i}_{\mathrm{daily,capital}}} \right\} \tag{5}$$

where $C^{\mathrm{DG},i}_{\mathrm{daily,capital}}$ is the daily capital cost of *i*th DG, *noDG* is the number of DGs installed in the community's MG, *t* is subscript indicating the hour index, $U_t^{\mathrm{DG},i}$ is a vector of binary integers representing unit status of *i*th DG at hour *t*, $P_t^{\mathrm{DG},i}$ is the output power of *i*th DG in kW at hour *t*, and $C^{\mathrm{DG},i,1}$ and $C^{\mathrm{DG},i,2}$ are the normalized daily purchase costs of *i*th DG in \$/h and \$/kWh, respectively.

- *Daily Start-Up Cost of DGs* $C^{\mathrm{DGs}}_{\mathrm{daily,start\text{-}up}}$: The daily start-up cost of DGs is determined from

$$C^{\mathrm{DGs}}_{\mathrm{daily,start\text{-}up}} = \sum_{i=1}^{noDG} \left(\sum_{t=1}^{24} SU_t^{\mathrm{DG},i} \cdot d^{\mathrm{DG},i} \right) \tag{6}$$

where $SU_t^{\mathrm{DG},i}$ is a vector of binary integers representing start-up status of *i*th DG at hour *t* and $d^{\mathrm{DG},i}$ is the start-up cost of *i*th DG in \$/start.

- *Daily Spinning Reserve Cost of DGs* $C^{\mathrm{DGs}}_{\mathrm{daily,spinning}}$: Total spinning reserve is the total amount of power generation available from all DGs, which are synchronized with the power grid, plus the available energy storage in ESS minus the load consumption [52]. The daily spinning reserve cost of DGs is determined from

$$C^{\mathrm{DGs}}_{\mathrm{daily,spinning}} = \sum_{i=1}^{noDG} \left(\sum_{t=1}^{24} R_t^{\mathrm{DG},i} \cdot r^{\mathrm{DG},i} \right) \cong \sum_{i=1}^{noDG} \left(\sum_{t=1}^{24} \left[\min\left\{ R10^{\mathrm{DG},i} \cdot U_t^{\mathrm{DG},i}, P_{\max}^{\mathrm{DG},i} \cdot U_t^{\mathrm{DG},i} - P_{\mathrm{t}}^{\mathrm{DG},i} \right\} \right] \cdot r^{\mathrm{DG},i} \right) \tag{7}$$

where $R_t^{\mathrm{DG},i}$ is the spinning reserve of *i*th DG at hour *t*, $r^{\mathrm{DG},i}$ is the reserve cost of *i*th DG in \$/kW, $R10^{\mathrm{DG},i}$ is the 10-min reserve capacity of *i*th DG, $P_{\max}^{\mathrm{DG},i}$ is the maximum power outputs of *i*th DG and min{*x*,*y*} returns the smallest value between either *x* or *y*.

With reference to eqs (5), (6) and (7), the DGs daily cost of community's MG is determined by the sum of the above three daily costs:

$$C^{\mathrm{DGs}}_{\mathrm{daily}} = C^{\mathrm{DGs}}_{\mathrm{daily,capital}} + C^{\mathrm{DGs}}_{\mathrm{daily,start\text{-}up}} + C^{\mathrm{DGs}}_{\mathrm{daily,spinning}} \tag{8}$$

C. Daily Cost of RESs

RESs are the green component of the community's MG. The intermittent and stochastic power generation obtained from the RESs, such as wind or PV systems of this paper, poses technical and economic obstacles when these are integrated in MGs. This is due to the insertion of significant uncertainties into the operation and power production planning of MGs [66]-[70].

To define the daily cost of RESs $C^{\mathrm{RESs}}_{\mathrm{daily}}$, there is a need of evaluating its two component daily costs, that are the daily cost of wind source and the daily cost of PV sources, namely [52]:

- *Daily Cost of Wind Source* $C_{\text{daily}}^{\text{Wind}}$: Wind power is currently the most widespread RES in the world.
  The daily cost of wind source is determined from
  $$C_{\text{daily}}^{\text{Wind}} = \sum_{t=1}^{24} U_t^{\text{Wind}} \cdot P_{\text{t}}^{\text{Wind}} \cdot c^{\text{Wind}} \tag{9}$$
  where U_t^{Wind} is a binary integer representing unit status of wind source at hour t, P_t^{Wind} is the output power of wind source in kW at hour t and c^{Wind} is the wind energy cost in \$/kWh.
- *Daily Cost of PV Source* $C_{\text{daily}}^{\text{PV}}$: PV power is high intermittent since it depends either on the day-night cycles or on the local weather conditions. In contrast with the wind sources, the generated power from PV systems represents a very low capacity percentage of the global power production at the moment.
  The daily cost of PV source is determined from
  $$C_{\text{daily}}^{\text{PV}} = \sum_{t=1}^{24} U_t^{\text{PV}} \cdot P_{\text{t}}^{\text{PV}} \cdot c^{\text{PV}} \tag{10}$$
  where U_t^{PV} is a binary integer representing unit status of PV source at hour t, P_t^{PV} is the output power of PV source in kW at hour t and c^{PV} is the PV energy cost in \$/kWh.

With reference to eqs (9) and (10), the RESs daily cost of community's MG is determined by the sum of the above two daily costs:

$$C_{\text{daily}}^{\text{RESs}} = C_{\text{daily}}^{\text{Wind}} + C_{\text{daily}}^{\text{PV}} \tag{11}$$

As it concerns the daily capital cost, daily start-up cost, and the daily maintenance cost of RESs, these are included in the energy costs c^{Wind} and c^{PV} as shown in eqs. (9) and (10), respectively (for more details, see in [49], [52]).

Note that, in accordance with [52], the investment cost of RESs is assumed equal to zero. This assumption is also maintained in this analysis so that direct comparisons among daily economic results of [52] can be given.

D. Daily Market Benefit

Communities and their grid-connected MGs actively participate in the energy market operations. In accordance with the buy/sell energy operations and the prices of the energy market, the optimization problem becomes the maximization of the daily TB TB_{daily}. Daily TB can be considered as the daily market benefit MB_{daily} minus the daily costs of community's MG, which have been already presented in Sections IVA-C.

As it concerns the evaluation of daily market benefit, it should be noticed that community's MGs can trade energy with the power grid and sell energy to the community's consumers.

In the case of the energy trade, the power grid can be considered as a bidirectional generator; it generates positive power when the power is transferred from the power grid to the community's MG whereas it generates negative power when the power is transferred inversely –*i.e.*, from the community's MG to the power grid–. This energy trade between community's MG and the power grid is limited by the capacity of the distribution lines that connect the community's MG with the power grid. Anyway, in the case of community's MGs, taking into account its system size, it is safely assumed that the power grid can always supply all the necessary reserves. In essence, community's MGs can free-ride on the power grid.

As it regards the consumers of the community's MG, their power consumption during the day is described by the power behavior of community's MG load $Load_t$. The energy sale to the consumers defines the benefit term of the consumer trade.

Therefore, the daily MB (MB_{daily}) consists of the daily market benefit due to the energy trade ($MB_{1,\text{daily}}$) and the daily market benefit due to the consumer consumption ($MB_{2,\text{daily}}$). Then, the daily MB is given by

$$MB_{\text{daily}} = \underbrace{\sum_{t=1}^{24}\left[-MP_t \cdot \sum_{i=1}^{noDG}\left(P_{\text{t}}^{\text{DG},i}\right)\right]}_{MB_{1,\text{daily}}} + \underbrace{\sum_{t=1}^{24}\left[MP_t \cdot Load_t\right]}_{MB_{2,\text{daily}}} \tag{12}$$

where MP_t is the energy market price.

E. Daily TB

The objective function of the technical module focuses on the maximization of the daily TB of community's MG. Already mentioned in Section IV(D), daily TB can be considered as the daily market benefit minus the daily costs of community's MG. With reference to eqs. (4), (8), (11) and (12), the daily TB is given from

$$TB_{\text{daily}} = MB_{\text{daily}} - C_{\text{daily}}^{\text{RESs}} - C_{\text{daily}}^{\text{DGs}} - C_{\text{daily}}^{\text{ESS}} \tag{13}$$

To maximize the daily TB of eq. (13), a set of technical constraints is required so that the operation of the components of community's MG is efficiently regulated. More specifically, these constraints, which are analytically presented in [52], are grouped into the following sets: (i) the real power balance concerning community's MG; (ii) the operation of DGs (minimum power production of larger online generator, maximum power production per DG $P_{\text{max}}^{\text{DG},i}$, i=1,..,$noDG$); (iii) the operation of ESS (minimum energy charged and discharged to ESS, minimum ESS spinning reserve capacity); and (iv) the combined operation of RESs with ESS (system spinning reserve, system 10-min operating reserve).

V. Economic Module

Historical weather data, load consumption, and market prices of the energy markets are easily available nowadays. Taking under consideration these input data and after applying the required technical constraints to the operation of community's MGs, the technical module establishes the basic economic case for community's MGs in a long-time horizon (baseline scenario).

However, long-term predictions suffer from significant divergences that can create either important daily TB differences or the technical stability loss of the community's MG. In addition, as it concerns the application of the technical module, there are certain additional constraints regarding its real-time application; taking under consideration the limited budget of a community and the required retrenchment concerning employee operating expenditures, there is a need of receiving simple and quick decisions regarding community's MG operation without seriously deviating from the baseline scenario and affecting its economic stability.

To establish a simple economic module, its related economic decisions doing with the consumption/generation attributes of ESS, DGs, RESs and power grid must satisfy the existing power needs without, however, violating the imposed technical constraints. Thus, by implementing a low-complexity and accurate economic module, there will be no need of real-time application of the technical module and, at the same time, the divergences from the initial optimal daily TB remain small and straightforward evaluated. Therefore, the simplicity of the economic module can capture the real life constraints sufficiently.

To support a simple economic module and to bypass the continuous use of the technical module, the decisions of the economic module must not influence the more complex sets of the technical constraints of the technical module (*i.e.*, the operation of ESS and the combined operation of RESs with ESS). Thus, the decisions of the economic module must focus on the operation of DGs, which is only limited by the relaxed technical constraint of the minimum capacity of larger online generator, and the evident constraint of maximum power production per DG, which follows the general constraint of the balance of the real power.

Based on the aforementioned concept, there are three different MG energy policies that can deal with the mitigation of the occurred power changes during the daily MG power generation or load consumption. These three different MG energy policies that are imposed by the economic module are: (i) MG Policy A: the power changes are first mitigated by the power grid and the remaining power part is adjusted through the operation of the already working DGs;
(ii) MG Policy B: the power changes are first mitigated by the operation of the working DGs and the remaining power part is channelized to the power grid; and
(iii) MG Policy C: the power changes are adaptively counterbalanced by the combined use of the working DGs and energy market. The participation percentage of DGs and energy market is set on a daily basis and remains fixed during the day.
This last MG policy combines the advantages of the adaptive systems and the manipulation simplicity of non-specialized personnel.

Although the technical module insists on defining the optimal mix among available ESS/DG/RES outputs and energy market, the economic module focuses on maintaining the community's MG operation near the proposed solution of the technical module providing, thus, a quasi-optimal solution. Actually, following the HTE model, three different scenarios describing potential power changes can be easily confronted, namely: (i) Scenario A: the load power consumption increases/decreases to *p*% with respect to the baseline scenario; (ii) Scenario B: the wind source production and/or PV source production increases/decreases to *p*% with respect to the baseline scenario; and
(iii) Scenario C: combined increases/decreases of the load power needs and RES power production with respect to the baseline scenario. In fact, the technical module of HTE model is an optimization model, where the constraints have a physical meaning, so its solution, which recommends the optimal power allocation over time, depends on the constraints and the objective function. If renewable power or load is changed, the binding constraints will change the optimal solution, and this will happen in a complex way since there are many binary variables involved. Applying the aforementioned three scenarios and assuming small divergences among real and predicted data,

the complex analysis of the technical module can be disregarded, since the MG can operate freely within capacity bounds giving a quasi-optimal solution.

VI. Discussion and Numerical Results

The simulation results of this Section aim at investigating: (i) the relation among real system parameters of community's MG, power production/consumption, and related financial data; (ii) the reaction of the HTE model against power production/consumption changes; and (iii) the assessment of the economic results when the aforementioned changes occur and different MG policies are applied.

In the following simulation results, a real community's MG is assumed during a typical day [52]. This MG consists of three main subcomponents (*i.e.*, ESS, DGs, and RESs) while its exact structure is detailed in [52]. Based on the real technical properties of [52] and [71], the properties of these subcomponents are synopsized as follows:

- In the case of ESS, the size of its BESS $S_{\mathrm{kWh}}^{\mathrm{BESS}}$ is equal to 500kWh, the purchase costs of BESS $C_{\mathrm{purchase,kW}}^{\mathrm{BESS}}$ and $C_{\mathrm{purchase,kWh}}^{\mathrm{BESS}}$ are assumed equal to 0$/kW and 600$/kWh, respectively, the interest rate r is equal to 6%, the ESS repayment period l is equal to three years and the maintenance cost of ESS $C_{\mathrm{maintenance}}^{\mathrm{ESS}}$ is assumed equal to 2000$. The maximum charge and discharge power limits are set at 50% of its full capacity. The minimum capacity is set at 10% of the full capacity (*i.e.*, 50kWh) while the maximum capacity is the full capacity of BESS (*i.e.*, 500kWh).
- In the case of DGs, there are two MTs (i=1,2) and one FC (i=3). The maximum power outputs of DGs $P_{\max}^{\mathrm{DG},1}$, $P_{\max}^{\mathrm{DG},2}$ and $P_{\max}^{\mathrm{DG},3}$ are equal to 2000kW, 1000kW and 1000kW, respectively, whereas their minimum power outputs $P_{\min}^{\mathrm{DG},1}$, $P_{\min}^{\mathrm{DG},2}$ and $P_{\min}^{\mathrm{DG},3}$ when they are online are equal to 100kW. The 10-min reserve capacities of DGs $R10^{\mathrm{DG},1}$, $R10^{\mathrm{DG},2}$ and $R10^{\mathrm{DG},3}$ are equal to 2000kW, 1000kW and 1000kW, respectively. The normalized daily purchase costs of DGs $\left[C^{\mathrm{DG},1,1},C^{\mathrm{DG},1,2}\right]$, $\left[C^{\mathrm{DG},2,1},C^{\mathrm{DG},2,2}\right]$ and $\left[C^{\mathrm{DG},3,1},C^{\mathrm{DG},3,2}\right]$ are equal to [30$/h, 0.13$/kWh], [50$/h, 0.35$/kWh] and [80$/h, 0.50$/kWh], respectively, the start-up costs of DGs $d^{\mathrm{DG},1}$, $d^{\mathrm{DG},2}$ and $d^{\mathrm{DG},3}$ are equal to 150$/start, 30$/start and 30$/start, respectively, and the reserve costs of DGs $r^{\mathrm{DG},1}$, $r^{\mathrm{DG},2}$ and $r^{\mathrm{DG},3}$ are equal to 0.010$/kW.
- In the case of RESs, there are one wind and one PV system:
  - For the wind system, its maximum power output $P_{\max}^{\mathrm{Wind}}$ is equal to 1000kW. The cut-in wind speed, the rated wind speed, and the cut-off wind speed are equal to 3m/s, 12m/s, and 30m/s, respectively.
  - For the PV system, the conversion efficiency of the solar cell array n is equal to 15.7% and its array area is equal to 7000m^2.

To compute the power output of wind and PV systems, real environmental data are considered: the forecast wind speed and solar radiation are presented in Fig.2 and Fig. 3 of [52], respectively. The wind energy cost c^{Wind} and the PV energy cost c^{PV} are assumed to be equal to 90$/MWh and 210$/MWh, respectively [32], [71].

As it has already been mentioned, the community's MG is connected to the power grid. Based on the load consumption and ESS/DG/RES power generation, this interconnection permits the community to buy and sell energy with the energy market. Actually, the community buys energy during the peak consumption periods and sells it during the valley consumption period while the limit of the power transfer between the community's MG and the power grid is set at 1000kW. Except for the energy arbitrage that can occur, the power grid offers the required reserve for the community's MG. To assess the economic impact of the energy arbitrage and power support, the energy market price is required. Based on real data [52], the energy market price is reported in Table 1.

Synoptically, the wind power output, the PV power output as well as their sum (*i.e.*, RES power output) are plotted with respect to the time during a day in Fig. 1(a). In Fig. 1(b), the RES power generation and the load power consumption of the community's MG are drawn with respect to the time [52]. In Fig. 1(c), the energy market price of the power grid, which is reported in Table 1, is curved with respect to the time.

Generalizing the observations of Fig. 1(a), it is obvious that the continuously growing amount of RESs influences the daily stability of power grids [67]-[69]. In contrast with DG systems, the power production of wind and PV systems is fluctuating. Although predictions have significantly been improved during the last years, an outage of multi-kW wind and PV farms poses a challenging problem [17], [72]-[82]. Hence, the RESs of the community's MG need to cooperate with contiguous ESS facilities in order to cope with their fluctuating nature. In addition, wind systems present more prevalent power production behaviors during the overnight hours in contrast with installed PV systems. Actually, the overnight hours are characterized by low power demand that is reflected on the low market prices of energy during these hours –see Fig. 1(c)–. Large ESSs and large energy trade with the power grid use can ameliorate the need for intermittent power generation sources to cover peak demand [11]. Moreover, from Fig. 1(b), it is evident that the RESs of the community's MG combined with the ESSs cannot be the sole provider of energy for the community's MG since the load consumption cannot be satisfied. Therefore, there is a need of an additional power production that can come from either the ESS/DGs of the community's MG or the power grid. The optimal mix among the different power sources is defined by the HTE model.

A. Baseline Scenario and the Implementation of the Technical Module of the HTE Model

The aforementioned key input parameters are inserted into the HTE model.

Table 1. Energy Market Price of the Power Grid

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Price ($/kWh)	0.11	0.10	0.11	0.09	0.11	0.11	0.13	0.15	0.26	0.30	0.35	0.40
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Price ($/kWh)	0.50	0.40	0.30	0.30	0.40	0.50	0.30	0.26	0.15	0.13	0.10	0.11

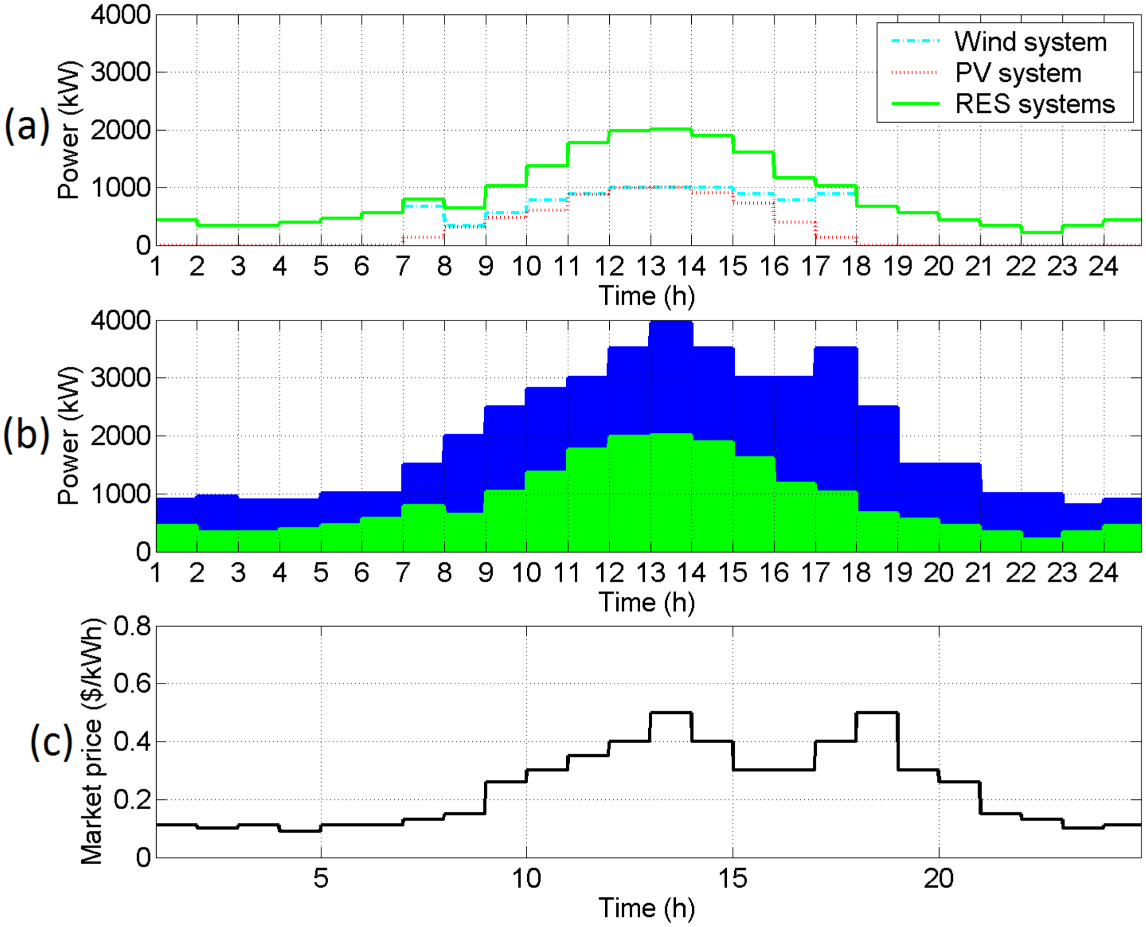


Figure 1. (a) Power production of RESs. (b) The contribution of RES power production (🟩) against load demand (🟦). (c) Energy market price.

To evaluate the optimal mix among available ESS/DG/RES outputs and energy market, the technical module of the HTE model appropriately combines these input parameters in a mixed-integer linear problem as presented in [52]. Prior to evaluate the daily TB of the community's MG as well as the other cost-related metrics, the first output of the technical module includes the power-related metrics, namely: the DG power output, the ESS power output with the energy stored in ESS as well as the exchanged power between community's MG and the power grid.

As it concerns the DG operation, the DG1 power output (*i.e.*, power output of MT1), the DG2 power output (*i.e.*, power output of MT2), the DG3 power output (*i.e.*, power output of FC), and their sum (*i.e.*, DG power output) are simultaneously plotted with respect to the time during a day in Fig. 2(a). In Fig. 2(b), the sum of DG power output and RES power output is drawn against the load power consumption with respect to the time.

As it concerns the ESS operation of the community's MG, in Figs. 3(a) and 3(b), its power output and its stored energy are plotted versus time during a day, respectively. In Fig. 3(c), the sum of ESS power output with DG and RES ones is curved against the load power consumption with respect to the time.

As it concerns the energy trade between community's MG and power grid, this is plotted versus time during a day in Fig. 4(a). In Fig. 4(b), the sum of the power grid trade with the power outputs of ESS, DG and RES is curved against the load power consumption with respect to the time.

Comparing Figs 2(a), 2(b), 3(a), 3(b), 4(a) and 4(b), interesting conclusions concerning the community's MG operation as well as the technical module optimization procedure can be deduced:

- Already mentioned, RESs of the community's MG cannot fully satisfy the community's power consumption. In order to enhance the power production of the community's MG, DG systems cooperate with RESs towards the mitigation of load consumption divergences. Based on the energy of ESS system, the DGs can be shut down during some time periods to save cost under the same technical constraints. However, the load consumption still remains unsatisfied during the day. Through the interconnection of the community's MG with the power grid, the community can buy power from the energy market when the energy market price is low and sell power to the power market when the energy market price is high and, at the same time, fixes the power differences between generation and consumption. Actually, the DG operation has been adjusted so that the aforementioned energy arbitrage can create revenues for the community while the power grid supports the system reserves of the community's MG.
- For an effective comparison, the starting and ending limits of ESS are set at its full capacity. Under this constraint, ESS only balances the power in the community's MG without supplying/absorbing extra energy to/from the community's MG, respectively. Clearly shown in Fig. 3(b), ESS supplies power to the community's MG during the peak load period while it is charged up during the low market price period. The energy stored in ESS will remain unchanged for the rest of the time.
- From Fig. 4(b), it is evident that the curves of power generation and power consumption of the community's MG are converging. Indeed, the optimal mix among the different power sources, which is defined by the technical module, satisfies the real power balance of community's MG.

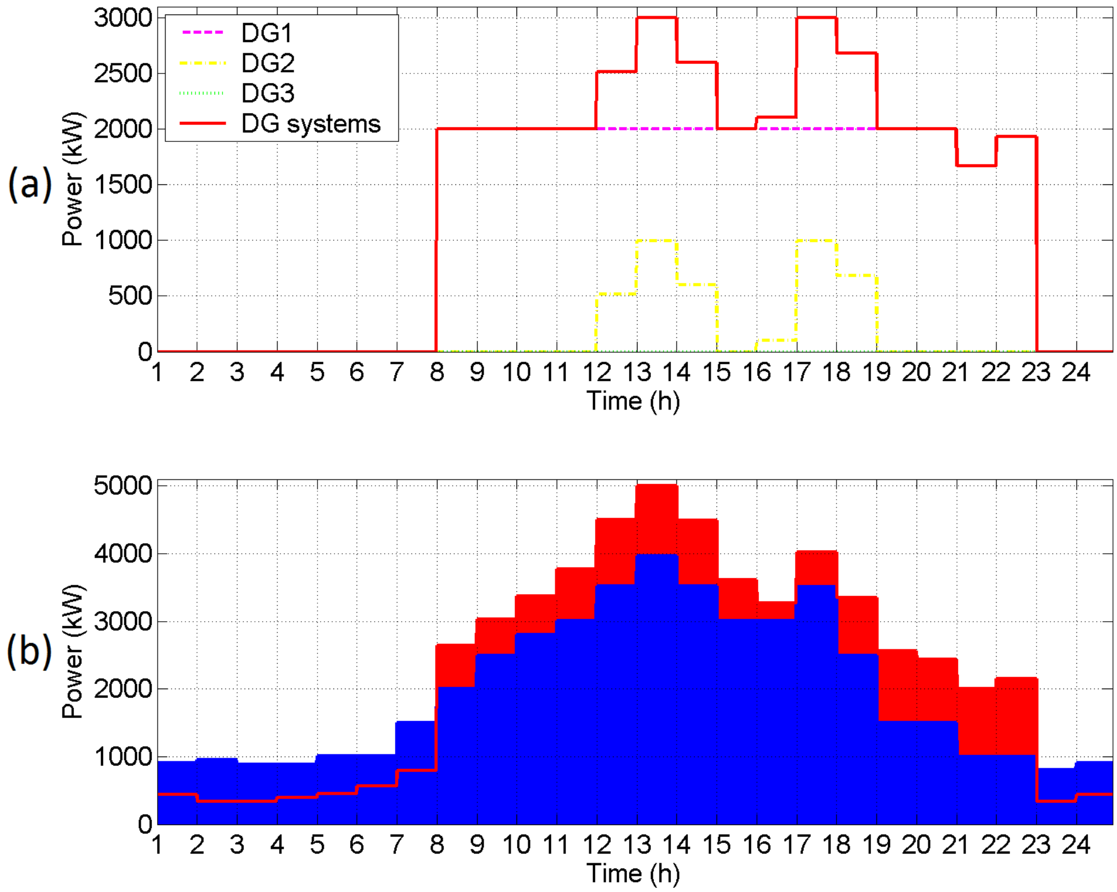


Figure 2. (a) Power production of DGs. (b) The contribution of DG and RES power production (🟥) against load demand (🟦).

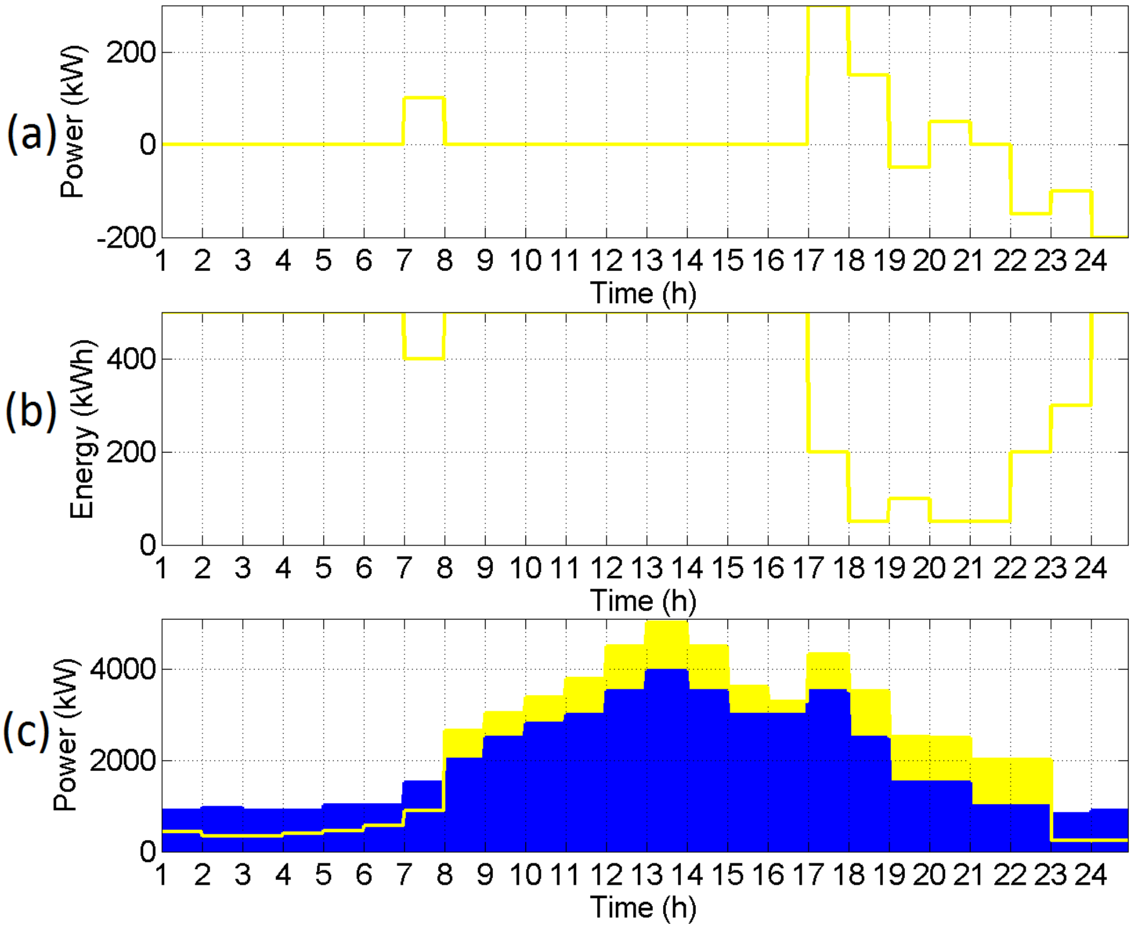


Figure 3. (a) Power production of ESS. (b) Energy stored in ESS. (c) The contribution of ESS, DG and RES power production (🟨) against load demand (🟦).

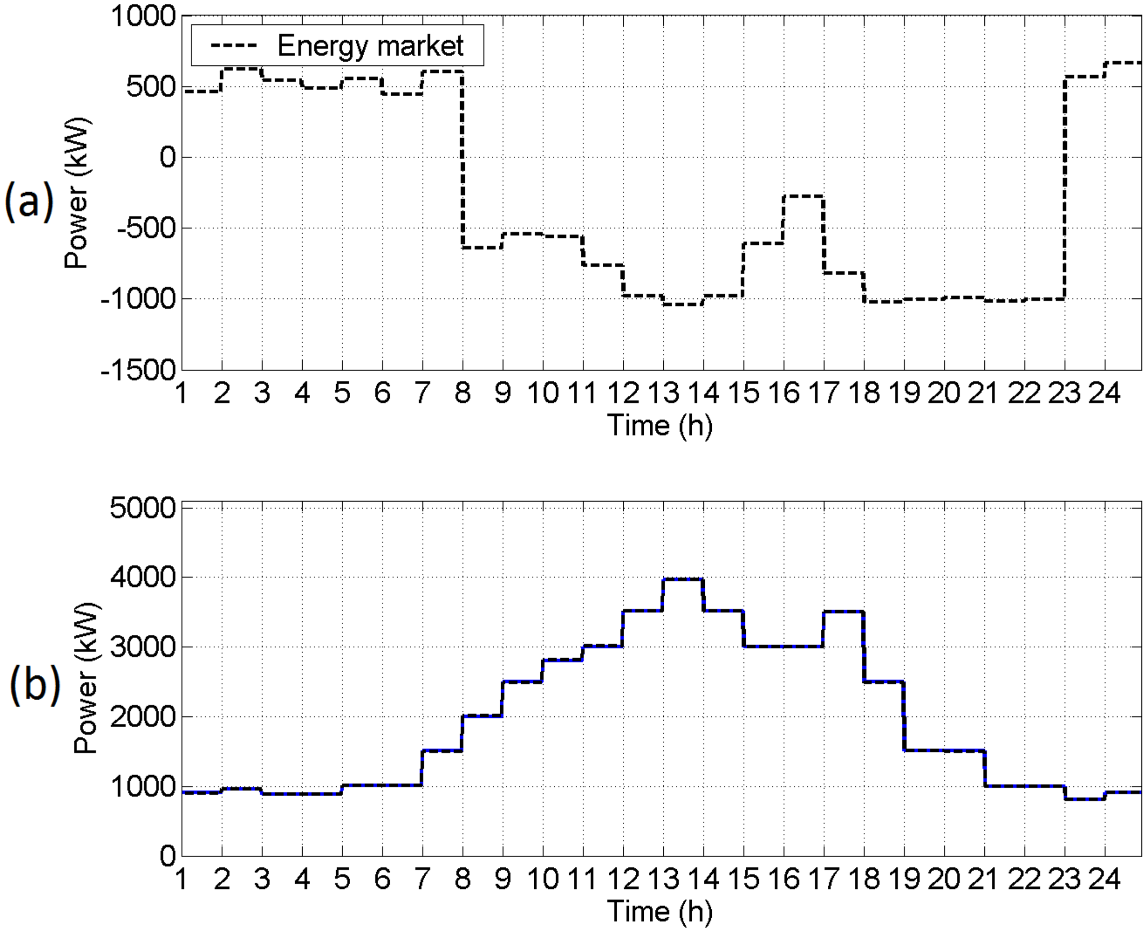


Figure 4. (a) Power exchange between community's MG and power grid. (b) The power production of power grid, ESS, DG and RES (▬ ▬) against load consumption (▬).

Apart from the power-related metrics, the main advantage of the technical module of the HTE model is that permits the correlation of these metrics with financial related ones. Although the latter metrics are valuable for economically describing the baseline scenario in this subsection, they are also used by the economic module in order to assess its supported MG policies.

The financial metrics, which are applied in this paper, can be further divided into three subgroups, namely: (i) the daily cost-related metrics; (ii) the daily gain-related metrics; and (iii) the daily TB. Based on these metrics and in order to investigate the financial behavior of the community's MG during the day, the cumulative version of these metrics is applied; the cumulative version describes the progressive absolute change of metrics during the day.

More analytically, in Fig. 5(a), the daily cost-related metrics that are the cumulative daily cost of ESS, the cumulative daily cost of DGs, the cumulative daily cost of RESs, and the cumulative total daily cost are plotted versus the time. The cumulative daily MB, the cumulative daily market benefit due to the energy trade (cumulative daily MB1) and the cumulative daily market benefit due to the consumer consumption

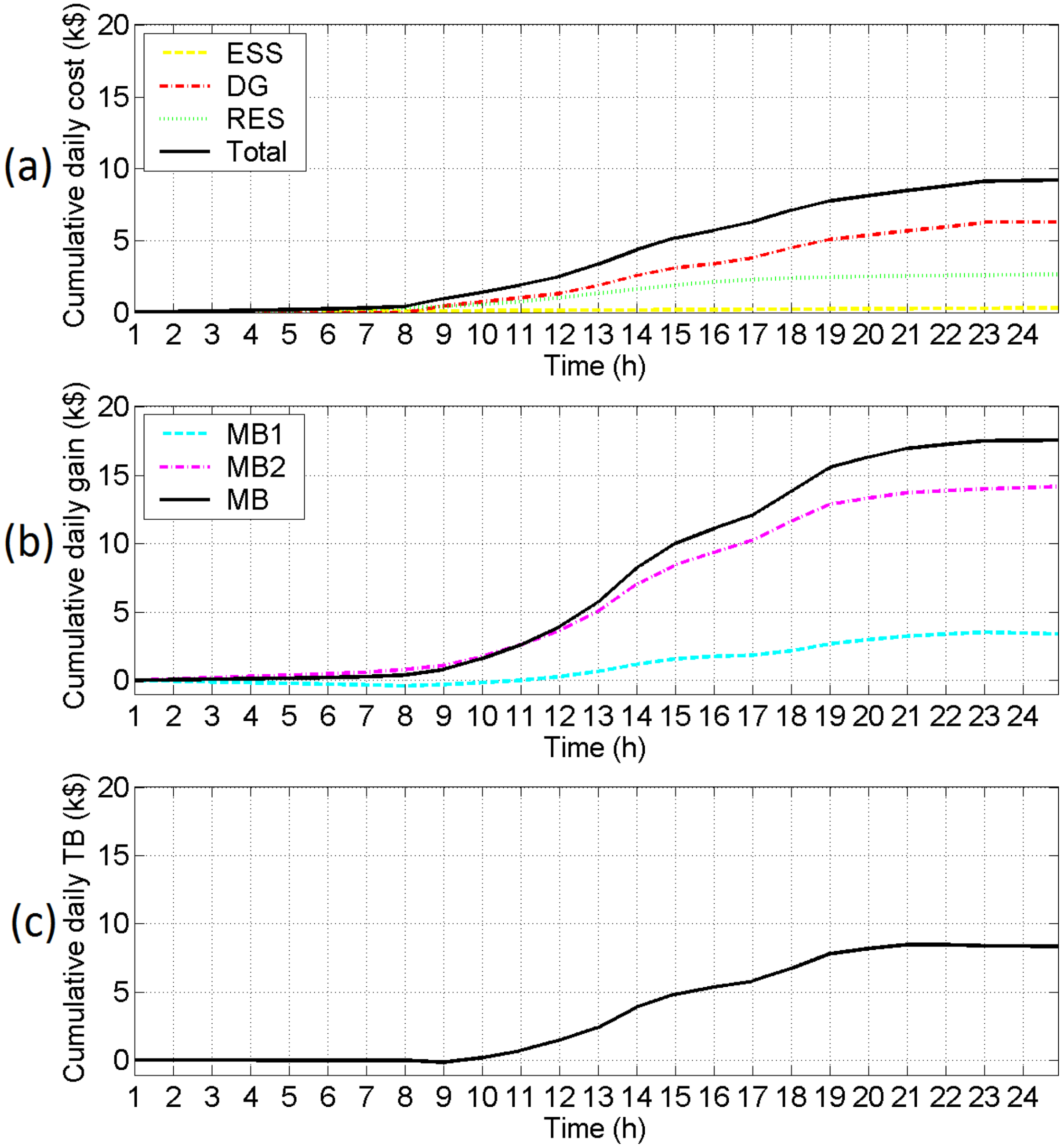


Figure 5. (a) Daily cost-related metrics. (b) Daily gain-related metrics. (c) Daily TB.

(cumulative daily MB2), which constitute the daily gain-related metric set, are drawn with respect to the time in Fig. 5(b). In Fig. 5(c), the cumulative daily TB is drawn versus the time.

From Figs. 5(a)-(c), several interesting remarks concerning the financial behavior of community's MG can be pointed out:

- The behavior of the different components of community's MG is reflected on the daily progress of their financial metrics as depicted in Fig. 5(a). First, the primary cost of community's MG is the cost related to the operation of DGs. This explains the reduced operation of all DGs, which is presented in Fig. 2(a); even if there are three DGs in the community's MG, only one of these (*i.e.*, DG1) operates from 8h to 23h. DG3 is permanently offline whereas DG2 sporadically operates (*i.e.*, from

12h to 15h and from 16h to 19h). Anyway, the start-ups of DGs are reflected on slope changes of DG daily cost. Second, the daily costs of ESS and RESs are significantly lower that the DG daily cost. Actually, these costs present a relatively stable cost behavior. The daily costs of ESS and RESs constitute only the 33% of the total cost.

- Due to their revenues, community's MGs are profitable investments and an interesting remedy against any financial difficulties and liquidity shortage that can be presented in communities. In fact, there are two different ways of collecting revenues when communities decide to deploy MGs: market benefit due to energy trade with the power grid (energy arbitrage) and the market benefit due to the energy sale to the consumers. As it concerns the energy arbitrage, it is now more obvious that: (i) the community purchases low-cost off-peak energy from 1h to 9h and sells it during periods of high prices, say from 10h to 20h; and (ii) the community increases the utilization of baseload DGs and decreases the use of peaking DGs [83]. In fact, the energy arbitrage can reach up to 25% of the MB that corresponds to approximately 5000$ per day. This is a significant amount that can cover different daily expenditures of the community.
- Based on the observations of Fig. 5(c), the main benefit occurs during the morning and afternoon hours whereas the ESS charging occurs during the night hours. Anyway, the technical module adjusts the operation of the community's MG components with the main objective of maximizing the daily TB. This is the reason for the very low TB during night hours; during these hours, the community buys energy from the power grid creating marginal financial losses (*i.e.*, TB remains below zero till 10h and TB decreases after 22h). TB increases till 21h, which is, anyway, validated by its positive slop. In addition, except for the TB, it is important to highlight the distinctive roles of power grid and ESS towards the stability of the community's MG. Finally, apart from the revenues from the energy arbitrage, a significant amount from the energy sale to the consumers inserts into the community's fund. In brief, the daily TB is equal to 8381$.

During a typical day, the community projects will collect approximately 8500$ per day. However, a crucial matter regarding the community's budget is the stability of these daily revenues from the community's MG. The financial stability helps towards a better financial planning and lower dependencies on banking loans so that the community's payments can be safely regulated.

B. The Philosophy behind MG Policies

As it has already been described, economic module helps towards the bypass of the complicated technical module. Towards that direction, the economic module can adopt one of the three available MG policies and can apply it to the power and financial results of the baseline scenario in order to mitigate any potential power change either in power production or in power consumption.

As it concerns MG policy A, its objective is to counterbalance the arisen power changes via the energy trade from the power grid while the remaining power part can be covered by the operation of the already working DGs. Observing Fig. 5(b), it is obvious that the energy arbitrage can reach up to 25% of the MB while the remaining 75% of the MB is defined by the energy sale to the consumers. The concept behind the MG policy A is that the coverage of the arisen power changes via the energy market mainly influences the gain of the energy arbitrage without directly affecting the power sale to the consumers. As it regards MG policy B, the objective is to cope with the arisen power changes via the operation of the already working DGs, and the remaining power part can be covered from the energy trade with the power grid. Observing Fig. 5(a), it is obvious that the DGs' cost can reach up to 67% of the total cost. The repletion of the power changes via the working DGs mainly focus on the DG cost. Actually, the reduction of DG operation hours can decrease the DG cost whereas increase of the operation hours of existing DGs exploit the economy of scale avoiding new start-up costs.

For MG policy C, this policy combines the strong points of MG policy A and B. Since the TB depends on gains and costs, an efficient policy could allocate the power changes either in gain factors or in cost factors. Hence, based on a fixed percentage allocation between DG operation and energy market on a daily basis, MG policy C compromises the power changes and the relevant financial results.

As it concerns the performance of MG policies, the objective of the HTE model is that for given power change *p*% in the daily MG power production or load consumption, the community still satisfies its daily power consumption while its daily TB change is maintained lower than *p*%. The efficiency of the aforementioned MG policies is going to be investigated in terms of their daily TB as well as their daily TB stability. The power changes that are examined are of the order of ±20%, which constitute typical upper and lower limits of power divergences between real and forecasted data.

C. Scenario A and MG Policies

Through its MG policies, the economic module provides quick and convenient suggestions against temporary power divergences either in production or in consumption avoiding the application of the complicated technical module. Among the stochastic variables of the community's MG, the load is a highly variable time-dependent parameter that critically influences the operation of the components of the community's MG and the TB. In order to examine the performance of MG policies against load instabilities, load changes of the order of +20% (upper load limits) and -20% (lower load limits) compared with the load consumption of the baseline scenario are assumed during the whole day.

In Figs. 6(a), 7(a) and 8(a), the cumulative daily cost is plotted versus the time for the upper, baseline and lower load limits when the MG policy A, B and C is adopted, respectively. Note that the power allocation between the power grid and the DG operation in MG policy C is assumed equal to 50%. In Figs. 6(b), 7(b) and 8(b), respective plots are given in the case of the cumulative daily gain while in Figs. 6(c), 7(c) and 8(c), respective plots are given in the case of the cumulative daily TB.

From Figs. 6(a)-(c), 7(a)-(c) and 8(a)-(c), it is obvious that the aforementioned three MG policies succeed in sustaining the financial stability of community's MG even in the most extreme power change cases of load consumption. With respect to the daily TB, MG policy B better manages the load increase of community's MG. Covering the arisen power needs through the more intensive operation of the already working DGs, MG policy B efficiently preserves the energy trade with the power grid, thus, protecting the revenues from the energy arbitrage. In contrast, when the load consumption decreases, MG policy B presents the worst TB results since the community's MG stops to exploit the cheap kWh of its DGs. During this system

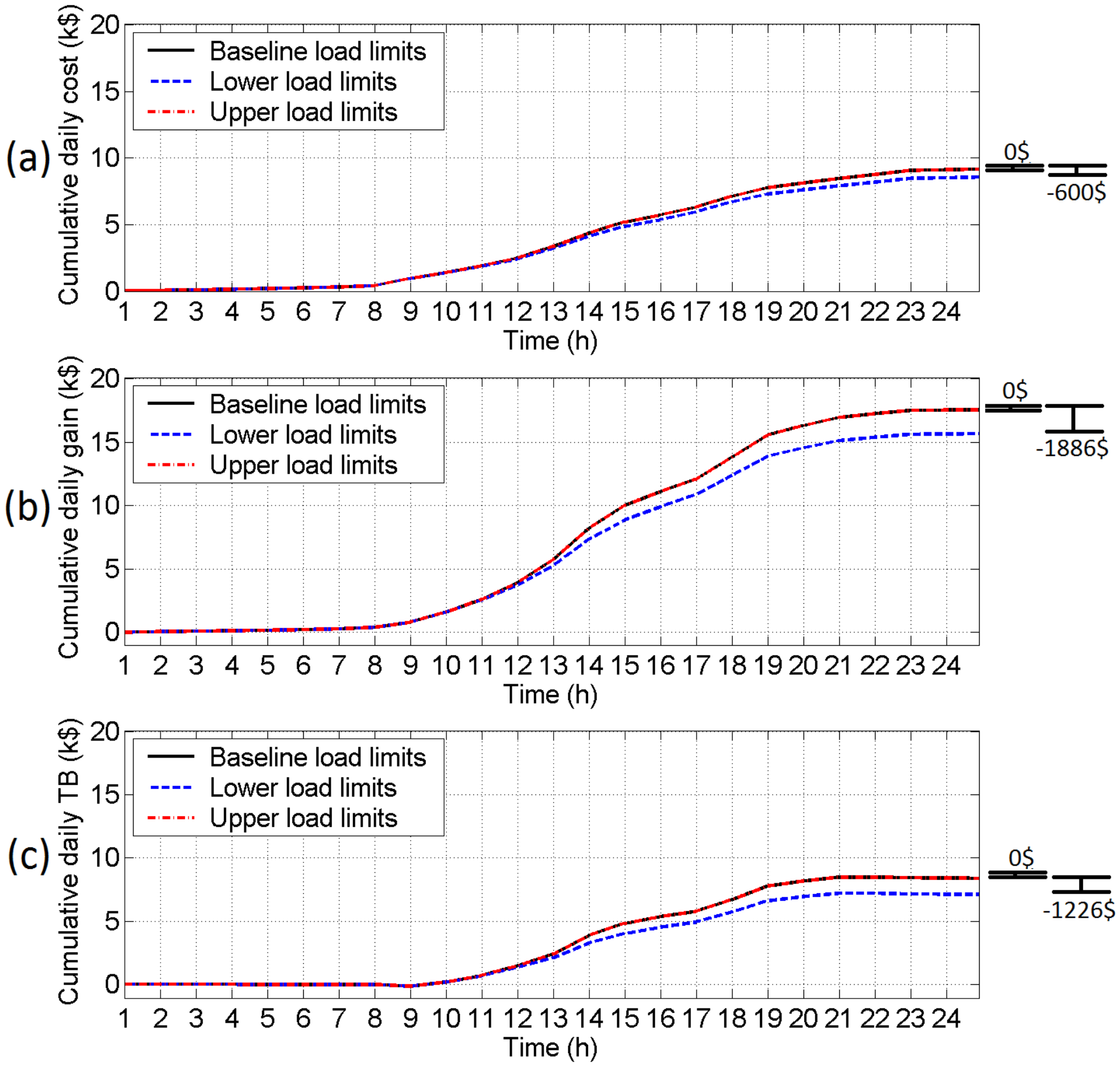


Figure 6. Financial metrics versus time for the scenario A when MG policy A is adopted. (a) Daily cost-related metrics. (b) Daily gain-related metrics. (c) Daily TB.

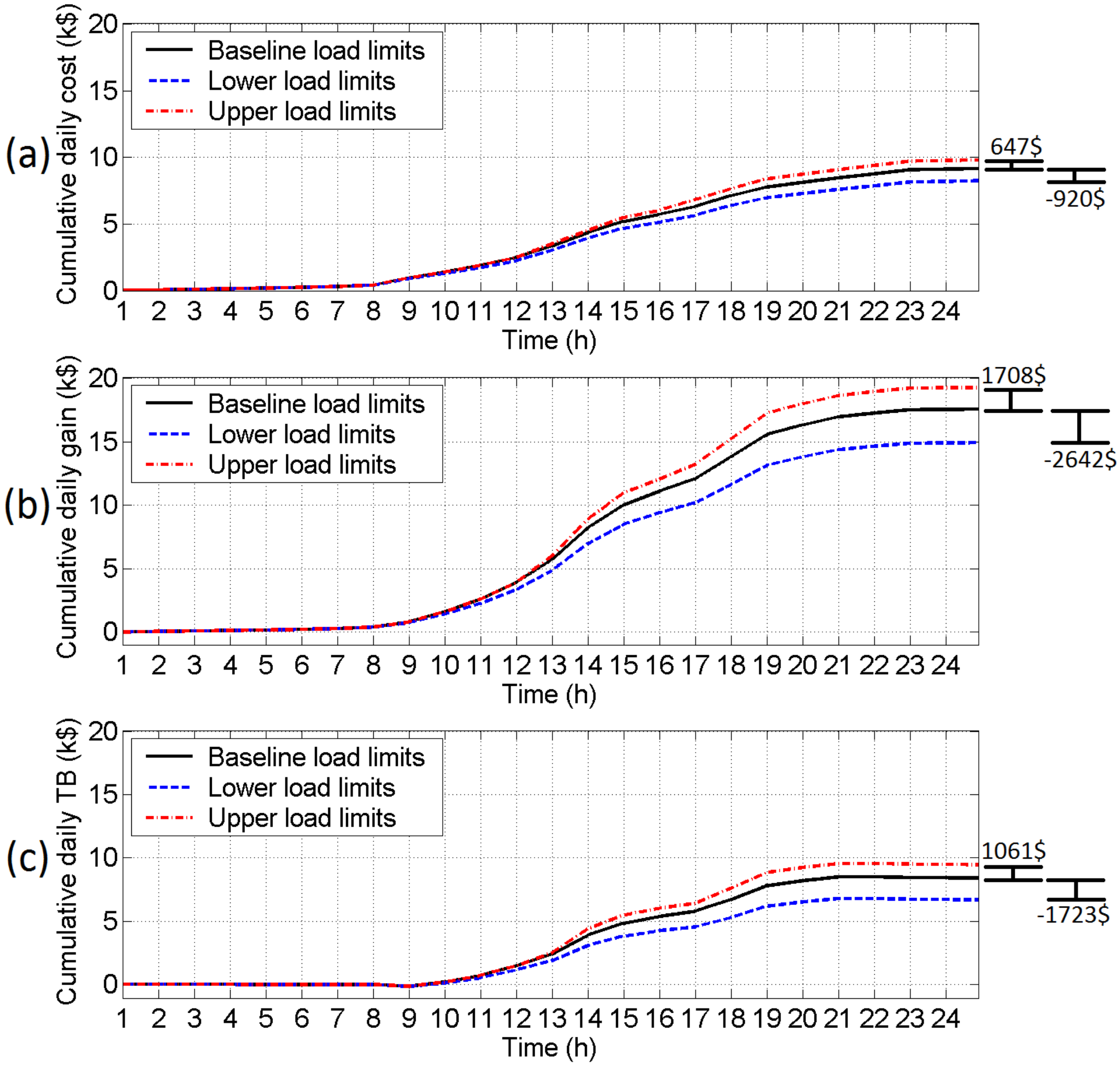


Figure 7. Same as in Fig. 6 but for MG policy B.

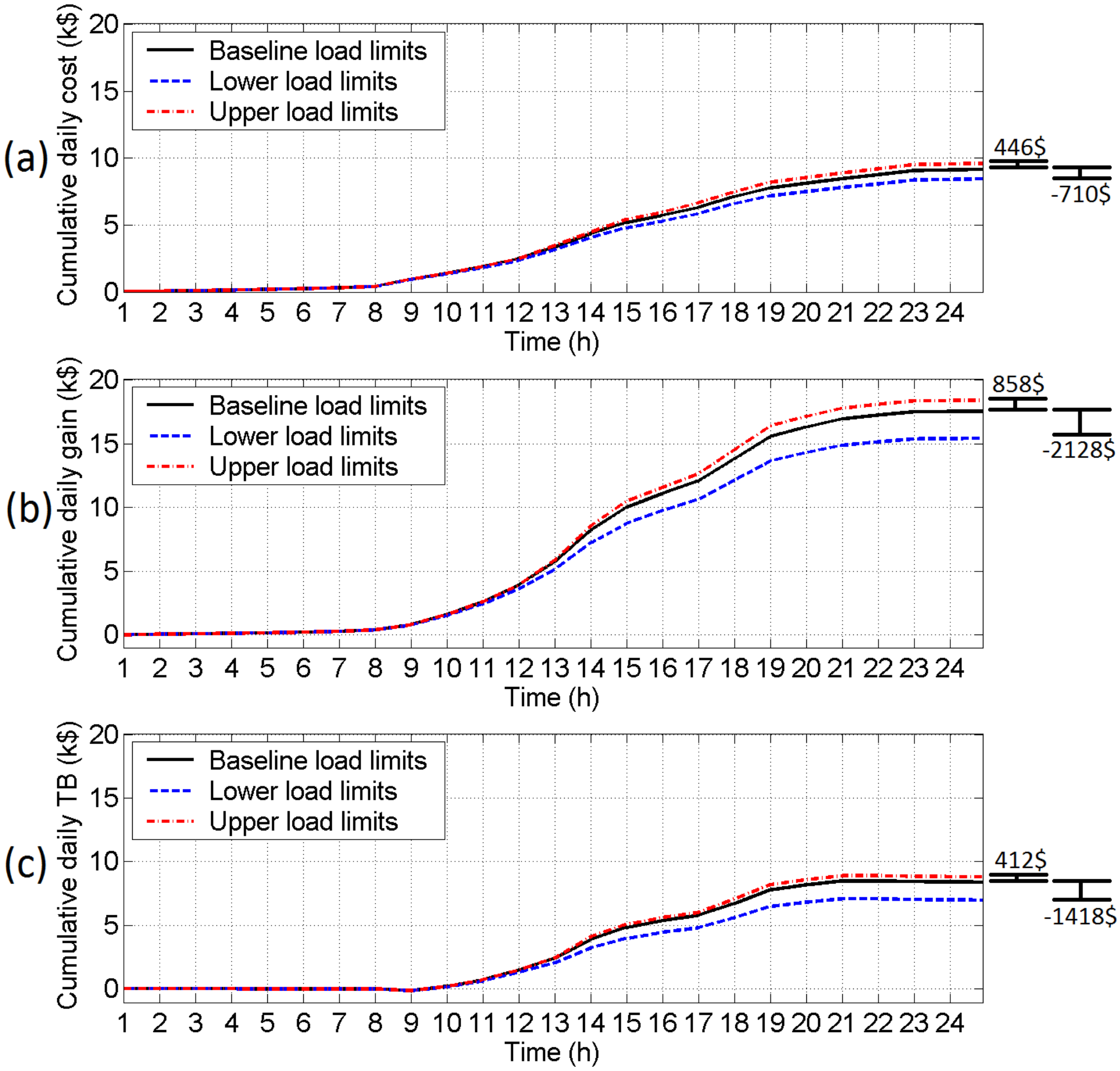


Figure 8. Same as in Fig. 6 but for MG policy C (the percentage allocation is equal to 50%).

condition, MG policy A better allocates the power differences between power grid and DG operation. MG policy A prefers the low cost power production of the DG operation selecting to channelize all load consumption differences through the reduction of energy trade with the power grid. Anyway, insisting on the DG operation, MG policy A jeopardizes the stability of the community's MG operation requiring further grid frequency regulation and power oscillation damping [35], [84]-[87].

MG policy C, which equally allocates the power needs between DG operation and power grid (*i.e.*, the allocation percentage is equal to 50%), presents a compromise between MG policy A and B with decent TB results in various load cases. However, the power change management of MG policy C could be further improved by exploiting its adaptive nature. More specifically, in Fig. 9(a), the daily cost is plotted versus the allocation percentage for the upper (+20%), case A (+10%), baseline, case B (-10%) and lower (-20%) load limits when the MG policy C is adopted. Note that the percentage

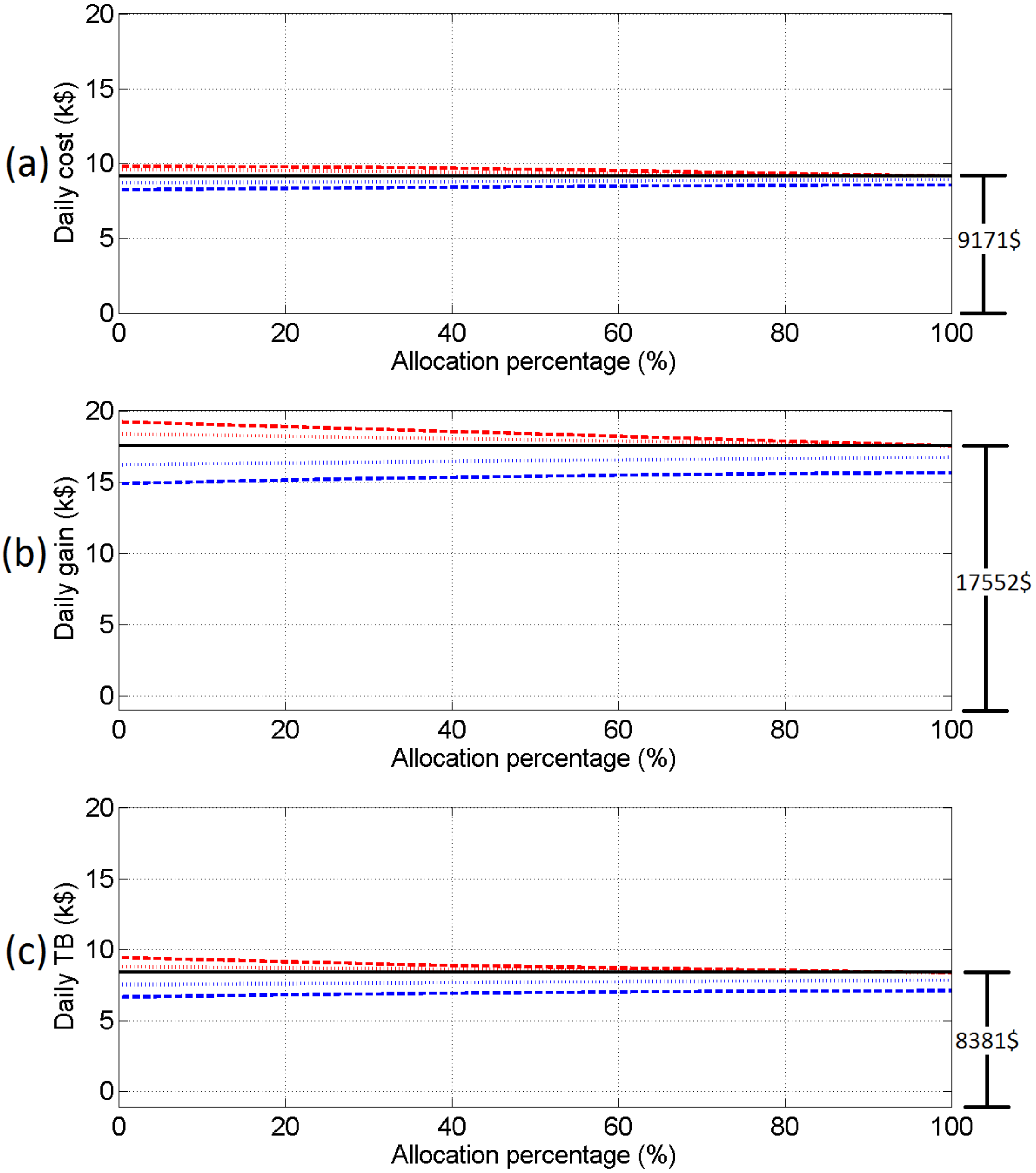


Figure 9. Financial metrics versus allocation percentage for the upper (- -), case A (''''''), baseline (—), case B (''''') and lower (- -) load limits when MG policy C is adopted. (a) Daily cost-related metrics. (b) Daily gain-related metrics. (c) Daily TB.

allocation describes the percentage of load difference that is covered by the power grid while the remaining power percentage corresponds to the power needs that are satisfied by the DG operation. In Figs. 9(b) and 9(c), respective plots are given in the case of the

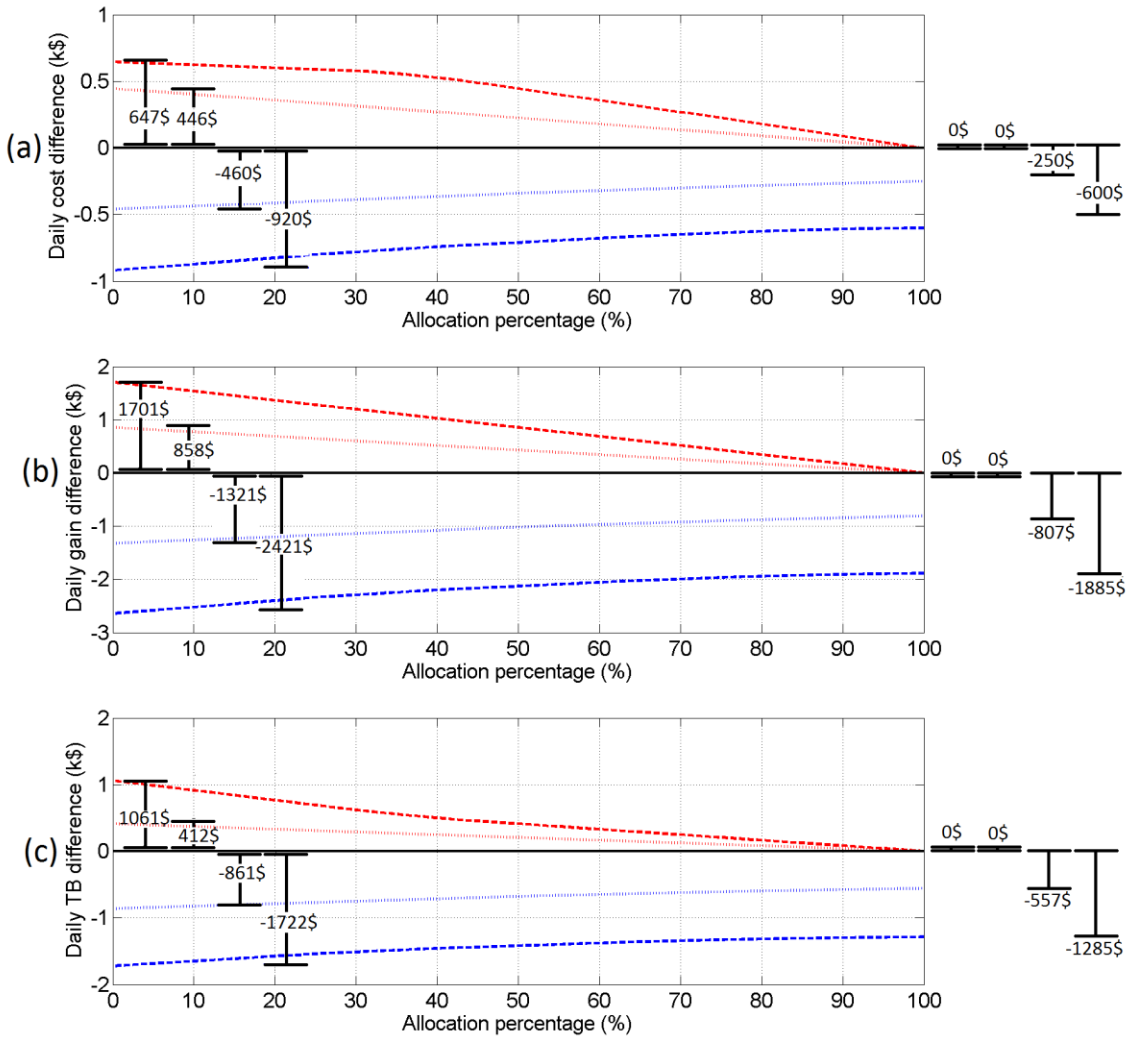


Figure 10. Differential financial metrics in comparison with the baseline scenario versus allocation percentage for the upper (▬ ▬), case A (''''''), baseline (▬), case B ('''') and lower (▬ ▬) load limits when MG policy C is adopted. (a) Daily cost-related metrics. (b) Daily gain-related metrics. (c) Daily TB.

daily gain and the daily TB, respectively. In Figs. 10(a)-(c), the daily cost difference, the daily gain difference and the daily TB difference in comparison with the baseline scenario are drawn with respect to the allocation percentage, respectively, when the MG policy C is applied for the upper, case A, baseline, case B, and lower load limits.

From Figs. 9(a)-(c) and 10(a)-(c), it is obvious that MG policy C, using its power allocation adaptability, achieves a better mitigation of load divergences in comparison with MG policy A and B in the community's MG. More specifically, in the case of the upper load limits, MG policy C creates maximum daily TB difference of 1061$ since it allocates all the power needs to the DG operation (*i.e.*, the allocation percentage is equal to 0%). This daily TB difference is greater than or equal to the respective daily TBs of MG scenario A and B, which are equal to 0$ and 1061$, respectively. Similarly, in the case of lower load limits, MG scenario C presents its best daily TB difference result, which is equal to -1285$, when it allocates all the power lacking to the power grid. Again, this daily TB is greater than or equal to the respective daily TB differences of MG scenario A and B, which are equal to -1286$ and -1723$, respectively. Actually, except for the upper and lower load limits, MG policy C efficiently imitates MG scenario B and A when load increases and decreases occur, respectively.

In addition, observing the dependence of daily TB on the allocation percentage, it is obvious that the daily TB rapidly diminishes as the allocation percentage increases when load consumption increases too. This dependence is almost linear. Conversely, the daily TB presents almost stable behavior for different allocation percentages when load consumption decreases. For given type of load changes (either load consumption increase or decrease), these behaviors remain the same regardless of the corresponding change percentage. Anyway, MG policy C can adaptively and easily change its allocation percentage depending on the load conditions so that better financial performance of community's MG can be achieved.

Until now, it is proven that the HTE model succeeds in satisfying the daily power consumption of the community's MG and in maintaining financially logical daily TB changes. Except for the daily power needs, the HTE model should maintain its daily TB change lower than *p*% for given power change *p*% in the daily load consumption. To examine this condition, in Table 2, the relevant difference of daily TB is investigated for different MG policies –*i.e.*, MG policy A, MG policy B, MG policy C (0%), MG policy (50%), and MG policy (100%)– when different load conditions occur (*i.e.*, upper, case A, baseline, case B and lower load limits).

From Table 2, it is validated that for given power change *p*% in the daily load consumption, the community still satisfies its daily power needs while its daily TB change is maintained lower than *p*% in the majority of the load scenarios examined. Negligible divergences of the order of 0.5% occur only in the case B and lower load limits when MG policy B and MG policy C (0%) are adopted. On the contrary, MG policy A and MG policy C (50%) guarantee higher financial stability than the other examined MG policies. Thus, the HTE model can be considered as a *quasi*-stable economic system for all MG policies that are supported by its economic module.

D. Scenario B and MG Policies

As it concerns the variable load conditions that can occur during the operation of a community's MG, the economic module provides quick and convenient solutions in order to mitigate them. Nevertheless, the efficiency of the economic module should be examined when temporary power divergences occur in the power generation. The main power sources that suffer from intermittency and power uncertainty are wind and PV systems; say, the RES power production of the community's MG.

RES production fluctuations occur due to: (i) variable weather conditions that affect wind and PV production; (ii) forecast data deviations either in wind speed or in solar radiation; and (iii) technical issues concerning the equipment and installation of RESs. In order to examine the performance of MG policies against RES power generation instabilities, power production changes of the order of +20% (upper load limits) and -20% (lower load limits) compared with the power production of the baseline scenario are assumed during the whole day. These power production changes are investigated for wind, PV and total RES systems.

Table 2. Relevant difference of daily TB (%) versus different MG policies and load conditions.

	Load conditions				
MG Policy	Upper (+20%)	Case A (+10%)	Baseline (0%)	Case B (-10%)	Lower (-20%)
A	0%	0%	0%	-6.6%	-15.3%
B	12.7%	4.9%	0%	-10.3%	-20.6%
C (0%)	12.7%	4.9%	0%	-10.3%	-20.6%
C (50%)	4.9%	2.5%	0%	-8.1%	-16.9%
C (100%)	0%	0%	0%	-6.6%	-15.3%

In Figs. 11(a)-(c), the cumulative daily TB of wind systems is plotted versus the time for the upper, baseline, and lower load limits when the MG policy A, B or C is adopted. Note that the power allocation between the power grid and the DG operation in MG policy C is assumed to be equal to 50%. In Figs. 12(a)-(c), respective plots are given in the case of the PV system while in Figs. 13(a)-(c), respective plots are given in the case of the total RES system.

From Figs. 11(a)-(c), 12(a)-(c) and 13(a)-(c), it is evident that the power changes of wind systems present higher TB impact in comparison with the respective ones of PV systems. This is due to the fact that the power production of wind systems extends during the whole day whereas the power production of PV systems is confined during the day hours. Anyway, regardless of the MG policy adopted, the TB impact of the power changes of the total RES system is significantly lower than the TB impact of load power changes (comparing with Figs. 6-8).

Although the daily TB fluctuations due to RES power production changes are generally low, MG policies A and B present the best TB results when RES power production increases and decreases, respectively. This is the opposite MG policy choice during the load changes. In brief, MG policy A is suitable for mitigating load decreases and RES power production increases whereas MG policy B is appropriate to counteract load increases and RES power production decreases.

As it has already been mentioned, adjusting its allocation percentage, MG policy C can efficiently deal with the RES power production increases and decreases. In Fig. 14(a), the daily TB is plotted versus the allocation percentage for the upper (+20%), case A (+10%), baseline, case B (-10%) and lower (-20%) RES power production when the MG policy C is adopted. In Fig. 14(b), the daily TB difference in comparison with the baseline scenario is drawn with respect to the allocation percentage when the MG policy C is applied for the upper, case A, baseline, case B. and lower RES power production.

From Figs. 14(a) and (b), it is obvious that MG policy C exploiting its power allocation adaptability better mitigates RES power generation divergences in

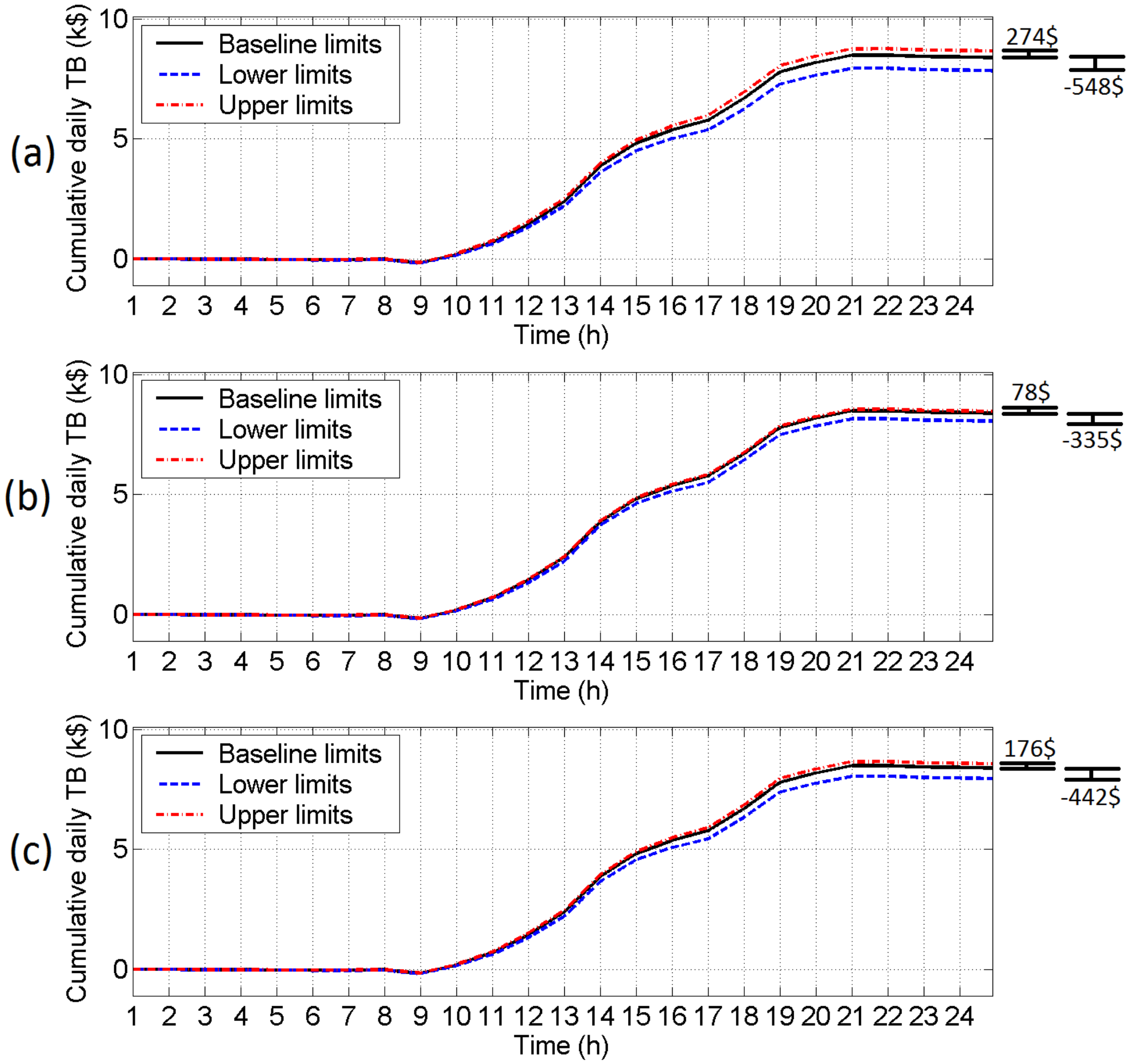


Figure 11. Daily TB versus time for the scenario B (wind system). (a) MG policy A. (b) MG policy B. (c) MG policy C (50%).

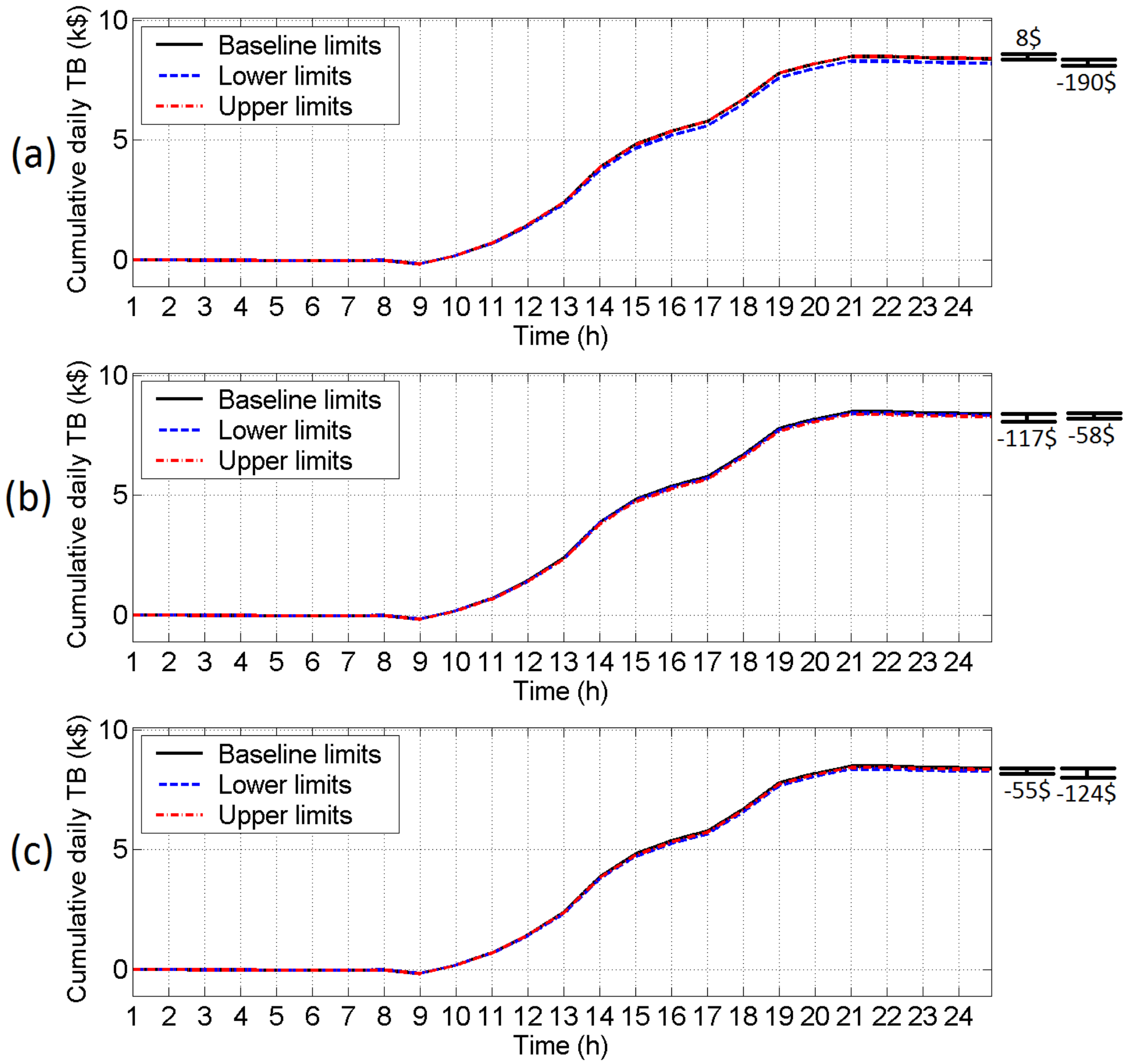


Figure 12. Same as Fig. 11 but for PV systems.

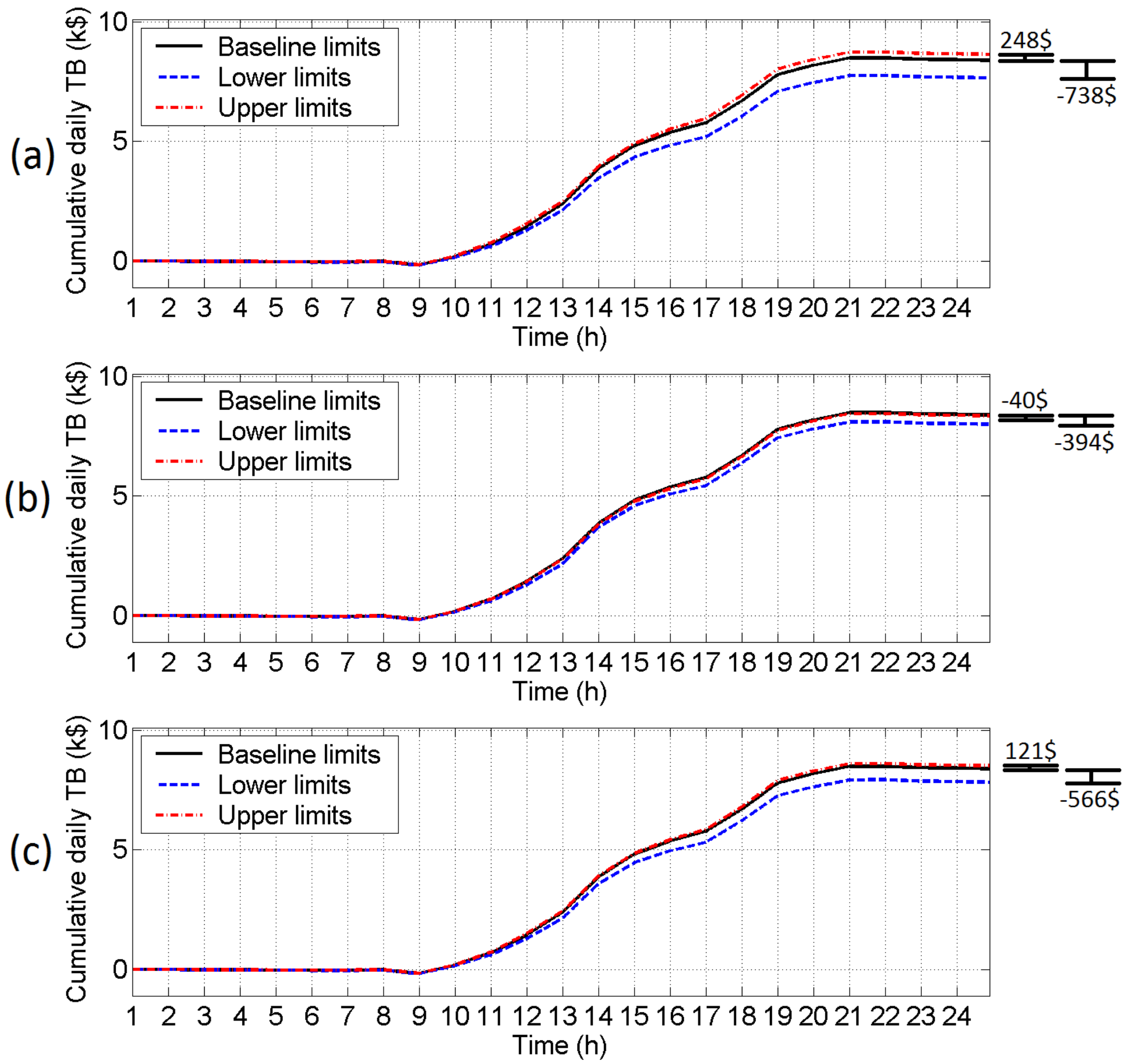


Figure 13. Same as Fig. 11 but for the total RES systems.

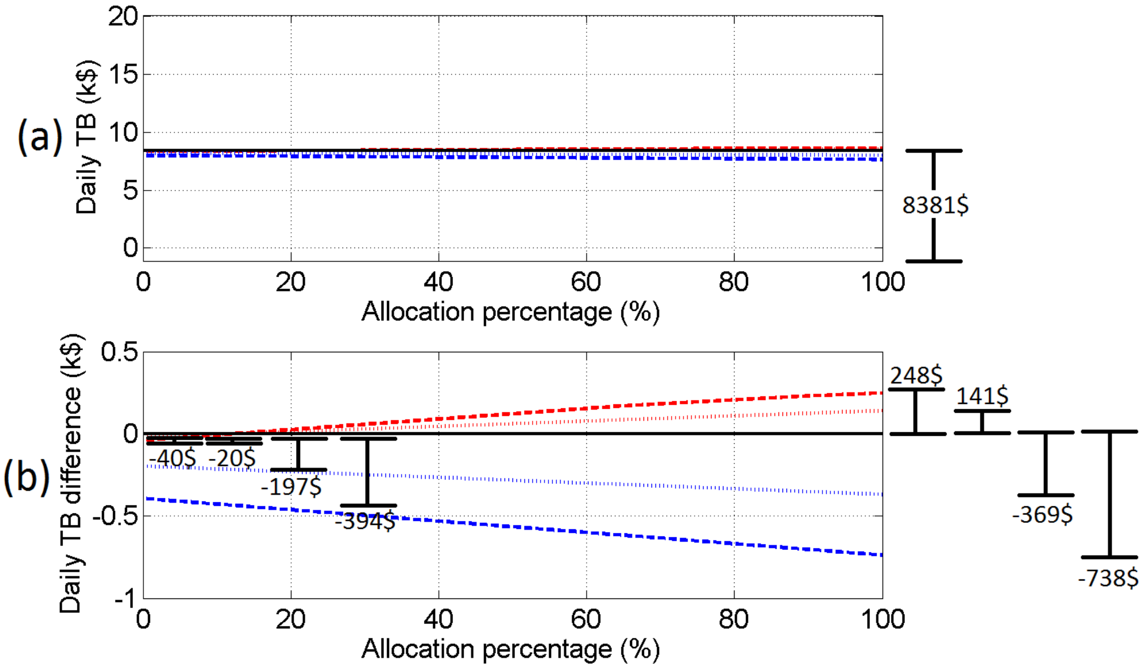


Figure 14. Financial and differential financial metrics versus allocation percentage for the upper (▬ ▬), case A (⋯), baseline (▬), case B (⋯) and lower (▬ ▬) RES power production when MG policy C is adopted. (a) Daily TB. (b) Differential daily TB.

comparison with MG policy A and B in community's MG. Similarly to the behavior against load changes, in the case of the upper RES power generation limits, MG policy C creates maximum daily TB of 8629$ selling all the power surplus to the energy market (*i.e.*, the allocation percentage is equal to 100%). This daily TB is greater or equal to the respective daily TB of MG scenario A and B. Similarly, in the case of lower RES power generation limits, MG scenario C presents its best daily TB result, which is equal to 7987$, when it removes all the power lacking from the cheap kWh of the DG operation. Again, this daily TB is greater or equal to the respective daily TB of MG scenario A and B. Actually, the same behavior of MG policy C occurs when different RES power generation limits are considered.

Moreover, the dependence of daily TB on the allocation percentage presents almost linear behavior regardless of the change of RES power production. Anyway, MG policy C can adaptively and easily change its allocation percentage depending on the RES production so that better financial performance of community's MG is achieved.

Similarly to load changes, the HTE model should maintain its daily TB change lower than *p*% for given RES power production change *p*%. To examine this condition, in Table 3, the relevant difference of daily TB is investigated with regard to the adopted MG policy –*i.e.*, MG policy A, MG policy B, MG policy C (0%), MG policy (50%), and MG policy (100%)– when different RES power production conditions occur (*i.e.*, upper, case A, baseline, case B, and lower load limits).

From Table 3, it is verified that for given power change *p*% in the daily RES power production, the community still satisfies its daily power consumption while

Table 3. Relevant difference of daily TB (%) versus different MG policies and RES power production conditions.

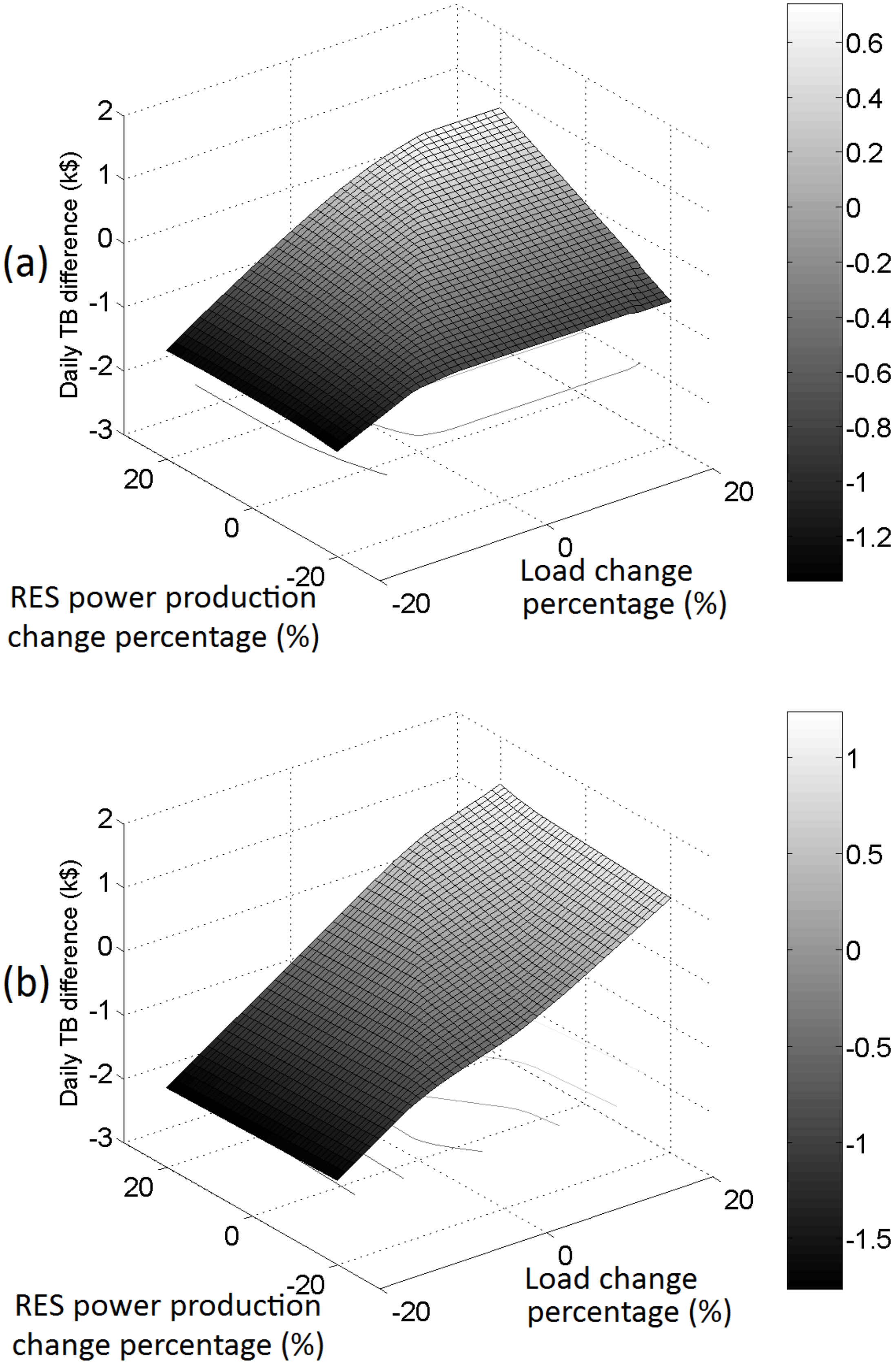
Relevant difference of daily TB (%)	RES power production conditions				
MG Policy	Upper (+20%)	Case A (+10%)	Baseline (0%)	Case B (-10%)	Lower (-20%)
A	3%	1.7%	0%	-4.4%	-8.8%
B	-0.5%	-0.2%	0%	-2.3%	-4.7%
C (0%)	-0.5%	-0.2%	0%	-2.3%	-4.7%
C (50%)	1.4%	0.7%	0%	-3.4%	-6.8%
C (100%)	3%	1.7%	0%	-4.4%	-8.8%

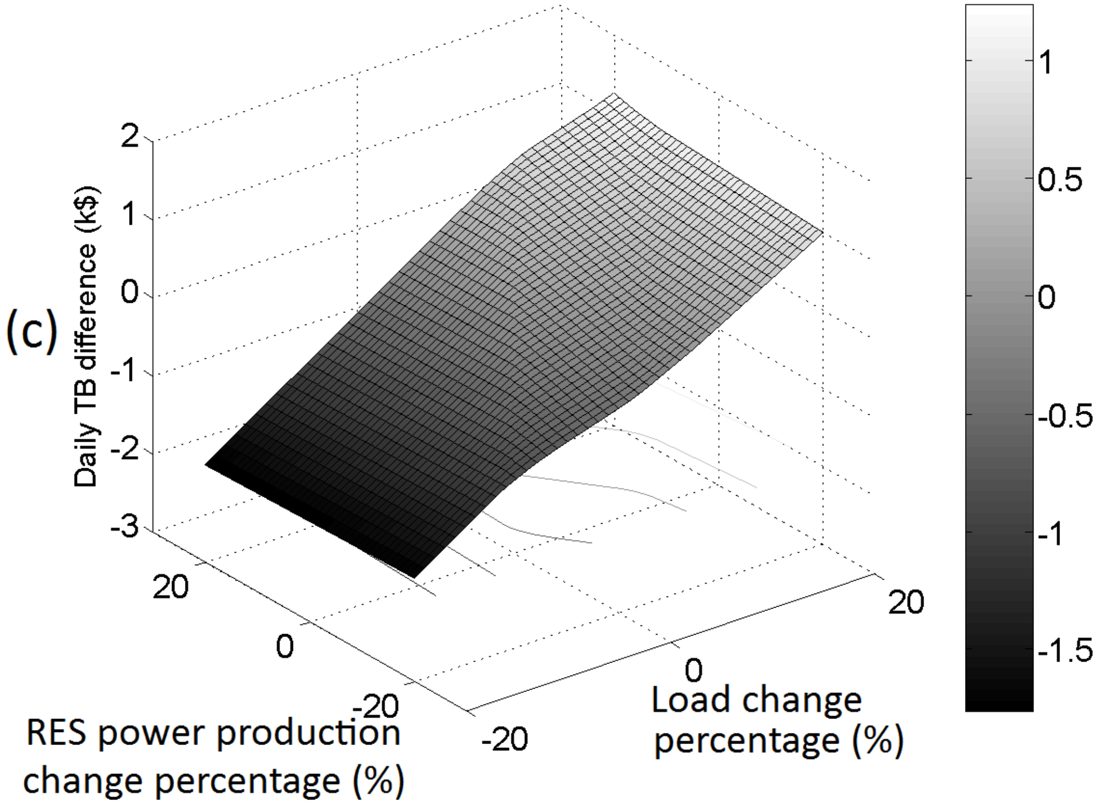
its daily TB change is maintained lower than *p*% in all the RES power production cases examined. Actually, comparing Tables 2 and 3, the daily TB changes due to RES power production changes are significantly lower than the respective ones of the load consumption. Hence, the HTE model outlines an economic stable system for all MG policies that are supported by its economic module.

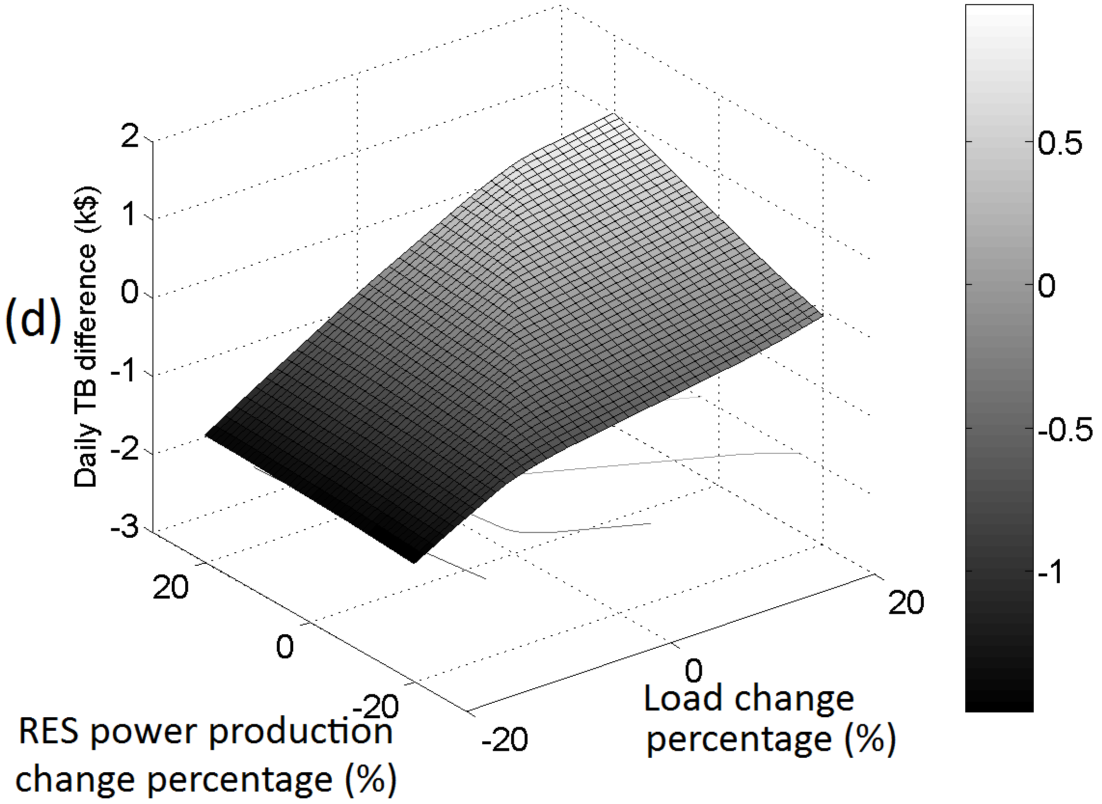
E. Scenario C and MG Policies

Although the economic module succeeds in maintaining controllable daily TB changes for given power change either in load consumption or in RES power production, the performance of the economic module should be examined in the case of simultaneous changes in load consumption and in RES power generation. The combined changes define a significantly more complicated power situation but this is a more realistic operation scenario for community's MGs.

To further investigate the behavior of the economic module, various combinations of scenarios A and B are examined. More specifically, in Figs. 15(a)-(e), the daily TB difference is plotted versus the RES power production change percentage and load change percentage for representative policies of the economic module –*i.e.*, MG policy A, MG policy B, MG policy C (0%), MG policy (50%), and MG policy (100%)–, respectively. Note that the RES power production change percentage and load change percentage present the relative change percentages in relation with the respective baseline scenario.


(a)
Daily TB difference (k$)
2
1
0
-1
-2
-3
20
0
-20
RES power production change percentage (%)
-20
0
20
Load change percentage (%)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
(b)
Daily TB difference (k$)
2
1
0
-1
-2
-3
20
0
-20
RES power production change percentage (%)
-20
0
20
Load change percentage (%)
1
0.5
0
-0.5
-1
-1.5


(c)
Daily TB difference (k$)
2
1
0
-1
-2
-3
20
0
-20
RES power production change percentage (%)
-20
0
20
Load change percentage (%)
1
0.5
0
-0.5
-1
-1.5


(d)
Daily TB difference (k$)
2
1
0
-1
-2
-3
20
0
-20
RES power production change percentage (%)
-20
0
20
Load change percentage (%)
0.5
0
-0.5
-1

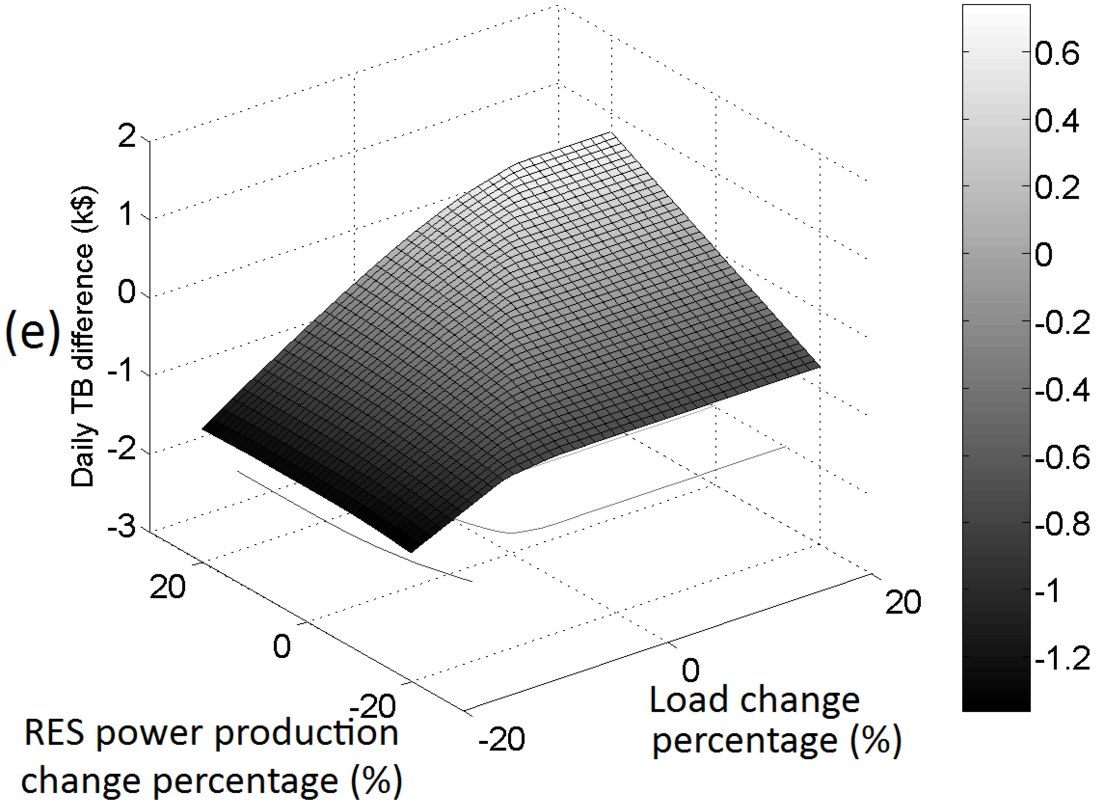


Figure 15. Daily TB difference versus RES power production change percentage and load change percentage when different MG policies are applied in comparison with the baseline scenario. (a) MG policy A. (b) MG policy B. (c) MG policy C (0%). (d) MG policy C (50%). (e) MG policy C (100%).

From Figs 15(a)-(e), it is verified that the TB performance is more influenced by the load changes rather than RES power production regardless of the MG policy followed. Actually, exploiting the energy arbitrage and the practicability of the economic module, significant TB benefits could occur in comparison with the TB of the baseline scenario. The aforementioned observations allow the communities to consider a relatively stable daily TB from community's MGs.

As it concerns the examined MG policies, the maximum daily TB difference of MG policy A, B, C (0%), C (50%), and C (100%) is equal to 737$, 1233$, 1233$, 978$, and 738$, respectively, whereas the minimum daily TB difference of MG policy A, B, C (0%), C (50%), and C (100%) is equal to -1361$, -1762$, -1762$, -1496$, and -1361$, respectively. Hence, the MG policy C (50%) offers the middle solution among the available MG policies. This is also validated by the mean daily TB difference; the mean daily TB difference of MG policy A, B, C (0%), C (50%), and C (100%) is equal to -331$, -211$, -211$, -269$, and -330$, respectively. Anyway, the allocation percentage of MG policy C can be adjusted in order to guarantee a fixed daily TB taking under consideration the imminent load consumption and RES generation changes via short-term predictions.

Despite the encouraging TB results, the HTE model should also maintain its daily TB change lower than *p*% for given RES power production change p_1% and load change p_2% where *p* is the maximum absolute percentage of p_1 and p_2. To examine this condition, in Table 4, the relevant difference of daily TB is reported with regard to the adopted MG policy –*i.e.*, MG policy A, MG policy B, MG policy C (0%), MG policy (50%), and MG policy (100%)– when different combinations of RES power production (*i.e.*, upper, case A, baseline, case B, and lower RES power production limits) and load (*i.e.*, upper, case A, baseline, case B, and lower load limits) conditions occur.

From Table 4, it is validated that for given *p%* power changes in the daily load consumption and RES power production, the community still satisfies its daily power needs while its daily TB change is maintained lower than *p*% in the vast majority of the cases examined. Few exceptions of the order of 0.5% only occur during lower load conditions when MG policy B and MG policy C (0%) are adopted. Anyway, MG policy C is proven to offer the required financial stability to the communities for all the cases examined. Therefore, the HTE model can confront complicated conditions of power consumption and generation, however, maintaining its financial stability for the MG policies that are supported by its economic module.

F. Practical Application Limits of the HTE Model

Apart from its financial performance, the practical efficiency of the economic module of the HTE model is assessed with regard to the mitigated range of load changes. Actually, the practicability of the economic module and, consequently, of the HTE model reaches up to the point that the technical constraints of the technical module that regulate the operation of community's MG still are satisfied. Therefore, the practical efficiency of the economic module of the HTE model is assessed with regard to the mitigated range of RES power production and load consumption. Towards that direction, the violations of technical constraints are plotted versus the RES power production change percentage and load change percentage for the representative policies of the economic module –*i.e.*, MG policy A, MG policy B, MG policy C (0%), MG policy (50%), and MG policy (100%)– in Figs. 16(a)-(e), respectively. Note that the technical constraints are equal to 24; say, one technical constraint corresponds to each operation hour.

From Figs. 16(a)-(e), certain remarks concerning the practical limits of the economic module can be pointed out:

- Regardless of the considered MG policy, the economic module successfully mitigates load differences that range from -47% to +26% with respect to the load consumption of the baseline scenario. Actually, this great range of load fluctuations covers the vast majority of load conditions that may occur during the operational life of a community's MG. Therefore, the adoption of the economic module of the HTE model during the community's MG operation becomes a realistic scenario.
- The economic module better counteracts load decreases rather than load increases. This is due to the fact that the technical module has already heavily burdened either several operating DGs or the power grid in order to reduce costs instead of equally allocating the load needs. Hence, the economic module more easily unloads than allocates load needs.

Table 4. Relevant difference of daily TB (%) versus different MG policies, RES power production conditions and load conditions.

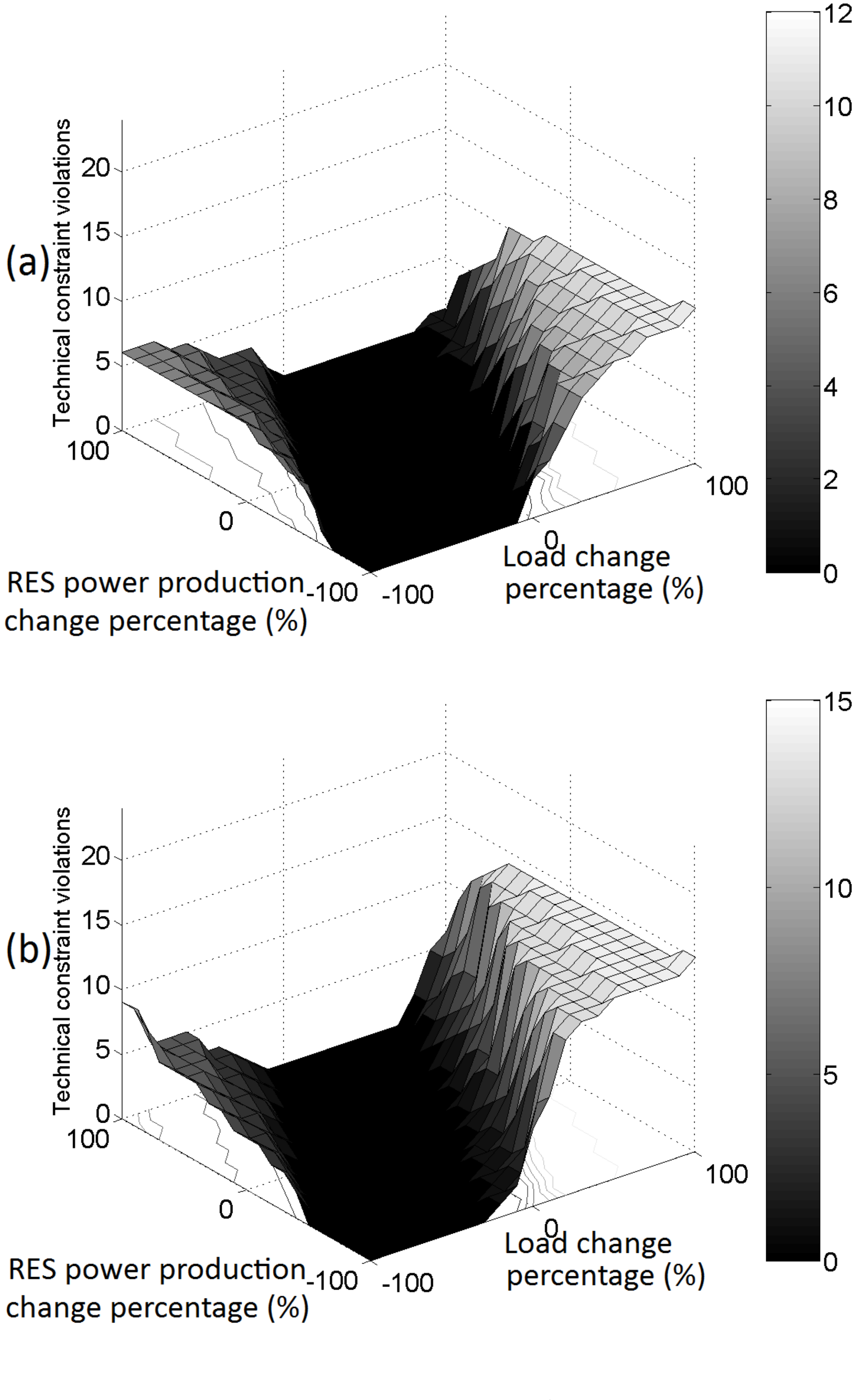
MG policy A	RES power production conditions				
Load conditions	Upper (+20%)	Case A (+10%)	Baseline (0%)	Case B (-10%)	Lower (-20%)
Upper (+20%)	8.8%	4.4%	0%	-4.4%	-9.2%
Case A (+10%)	8.5%	4.4%	0%	-4.4%	-8.8%
Baseline (0%)	3%	1.7%	0	-4.4%	-8.8%
Case B (-10%)	-5.7%	-6%	-6.6%	-7.8%	-9.5%
Lower (-20%)	-15.5%	-15.3%	-15.3%	-15.5%	-16.2%

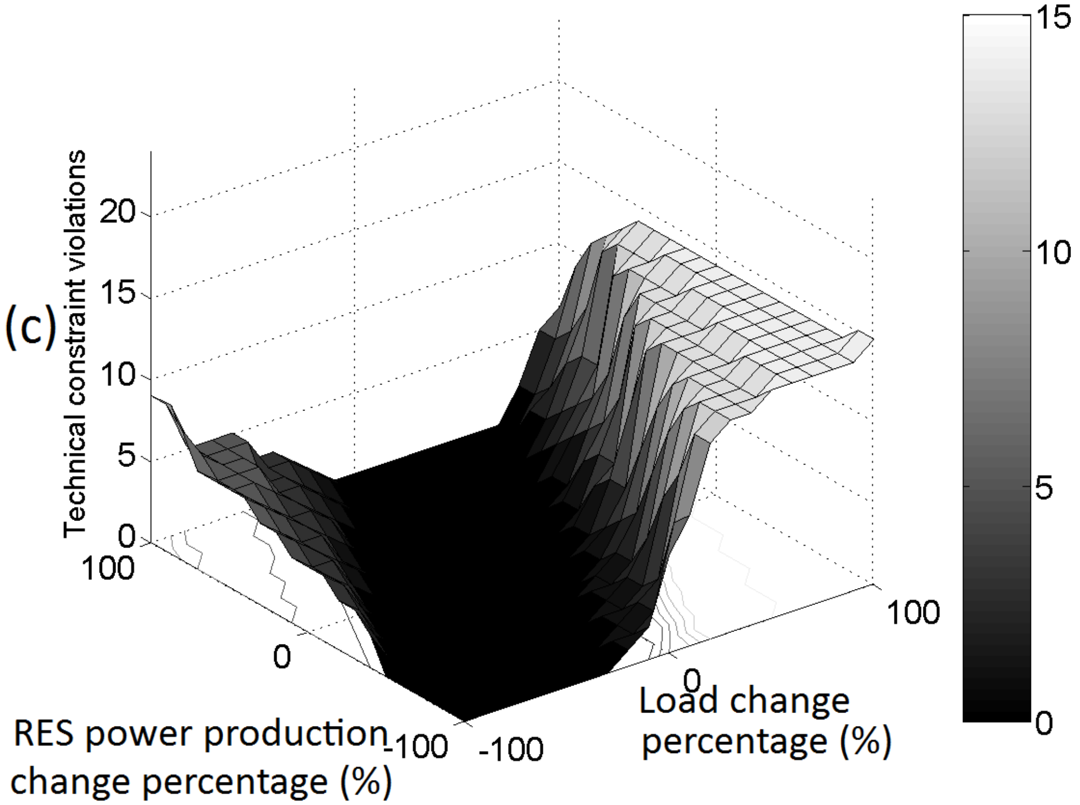
MG policy B	RES power production conditions				
Load conditions	Upper (+20%)	Case A (+10%)	Baseline (0%)	Case B (-10%)	Lower (-20%)
Upper (+20%)	14.7%	13.1%	12.7%	12.2%	11.6%
Case A (+10%)	9.2%	7.3%	4.9%	3.4%	2.9%
Baseline (0%)	-0.5%	-0.2%	0%	-2.3%	-4.7%
Case B (-10%)	-10.7%	-10.5%	-10.3%	-10%	-10.2%
Lower (-20%)	-21%	-20.8%	-20.6%	-20.3%	-20%

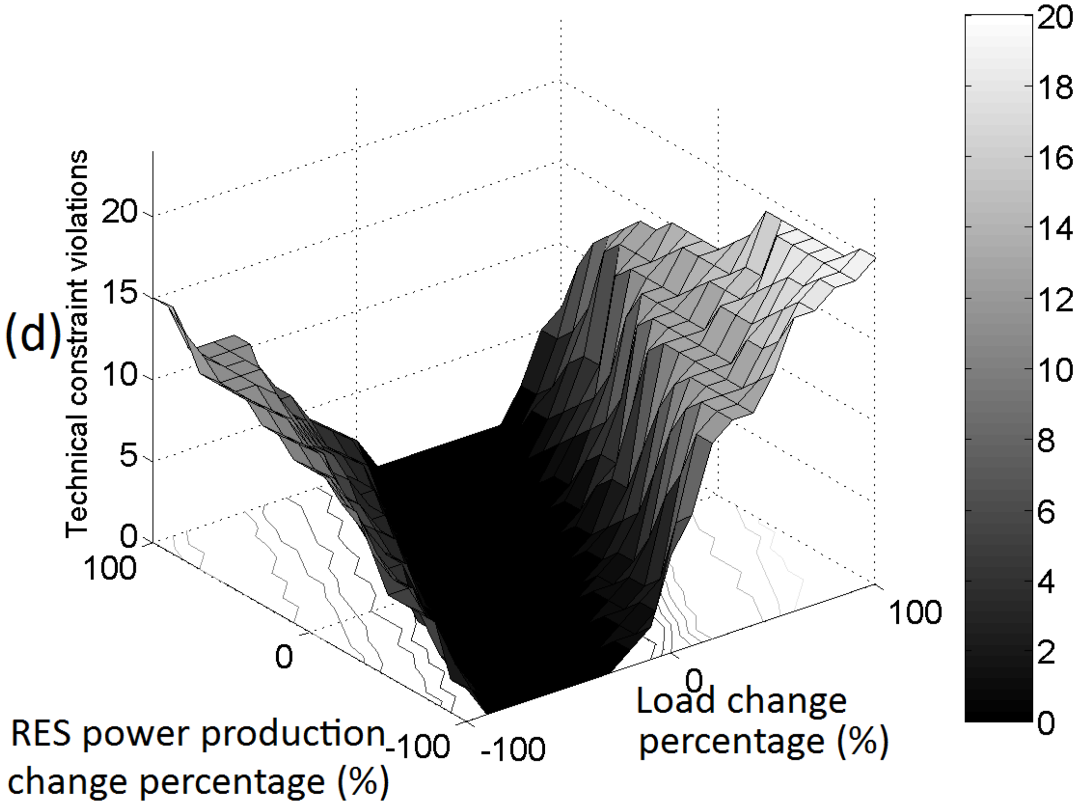
MG policy C (0%)	RES power production conditions				
Load conditions	Upper (+20%)	Case A (+10%)	Baseline (0%)	Case B (-10%)	Lower (-20%)
Upper (+20%)	14.7%	13.2%	12.7%	12.2%	11.6%
Case A (+10%)	9.2%	7.3%	4.9%	3.4%	2.9%
Baseline (0%)	-0.5%	-0.2%	0%	-2.3%	-4.7%
Case B (-10%)	-10.7%	-10.5%	-10.3%	-10%	-10.2%
Lower (-20%)	-21%	-20.8%	-20.6%	-20.3%	-20%

MG policy C (50%)	RES power production conditions				
Load conditions	Upper (+20%)	Case A (+10%)	Baseline (0%)	Case B (-10%)	Lower (-20%)
Upper (+20%)	11.7%	8.3%	4.9%	1.7%	-1%
Case A (+10%)	8.9%	5.8%	2.5%	-0.9%	-4.3%
Baseline (0%)	1.4%	0.7%	0	-3.4%	-6.8%
Case B (-10%)	-7.2%	-7.5%	-8.1%	-8.8%	-9.9%
Lower (-20%)	-16.5%	-16.6%	-16.9%	-17.3%	-17.8%

MG policy C (100%)	RES power production conditions				
Load conditions	Upper (+20%)	Case A (+10%)	Baseline (0%)	Case B (-10%)	Lower (-20%)
Upper (+20%)	8.8%	4.4%	0%	-4.4%	-8.8%
Case A (+10%)	8.5%	4.4%	0%	-4.4%	-8.8%
Baseline (0%)	3%	1.7%	0%	-4.4%	-8.8%
Case B (-10%)	-5.7%	-5.9%	-6.6%	-7.8%	-9.5%
Lower (-20%)	-15.5%	-15.3%	-15.3%	-15.5%	-16.2%


(a)
Technical constraint violations
0
5
10
15
20
100
0
-100
-100
0
100
RES power production change percentage (%)
Load change percentage (%)
0
2
4
6
8
10
12
(b)
Technical constraint violations
0
5
10
15
20
100
0
-100
-100
0
100
RES power production change percentage (%)
Load change percentage (%)
0
5
10
15


(c)
Technical constraint violations
0
5
10
15
20
RES power production change percentage (%)
100
0
-100
Load change percentage (%)
-100
0
100
0
5
10
15


(d)
Technical constraint violations
0
5
10
15
20
RES power production change percentage (%)
100
0
-100
Load change percentage (%)
-100
0
100
0
2
4
6
8
10
12
14
16
18
20

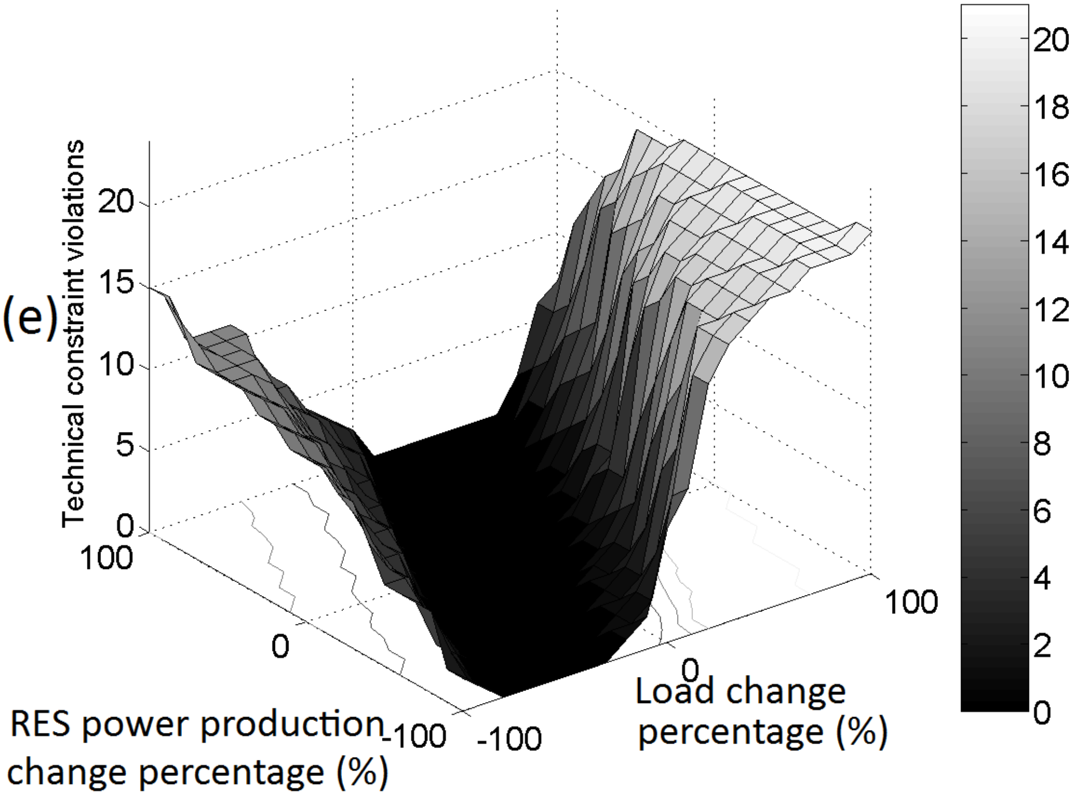


Figure 16. Technical constraint violations versus the RES power production change percentage and load change percentage when different MG policies are applied. (a) MG policy A. (b) MG policy B. (c) MG policy C (0%). (d) MG policy C (50%). (e) MG policy C (100%).

- Although MG policy C presents favorable characteristics concerning its TB performance and its financial stability, it suffers from high rate of technical constraint violations as load fluctuations significantly increase. In fact, a trade-off between TB and technical constraint violations is highlighted that is also observed in MG policy A and B: As the load increases, MG policy B demonstrates higher TB and higher number of technical constraint violations in comparison with the respective values of MG policy A.
- As it concerns the RES power production change percentage, it is demonstrated that the economic module successfully achieves to mitigate RES power production differences that range from -49% to 94% with respect to the RES power production of the baseline scenario. Actually, this range is significantly larger than the respective one of load fluctuations and practically allows the exclusive power change management of RESs through the economic module of the HTE model.
- In contrast with the load changes, the economic module can comfortably counteract either RES power production increases or decreases. This is due to the fact that the RES production changes are significantly lower in absolute numbers than those of load consumption. However, the trade-off between TB and technical

constraint violations is also observed in RES systems among different MG policies supported by the economic module.

- In the case of the combined fluctuations of load consumption and RES power production, it is shown that economic module achieves to cope with a great range of potential generation and consumption cases in the community's MG life. More specifically, the economic module succeeds in bypassing the technical module of the HTE model (*i.e.*, the technical constraint violations are equal to zero) in the 52.4%, 44.7%, 44.7%, 34.7%, and 34.2% of the cases when MG policy A, MG policy B, MG policy C (0%), MG policy (50%), and MG policy (100%) is applied, respectively. Hence, apart from the financial stability, economic module can successfully mitigate great changes either in power production or in power consumption.

VII. General Remarks and Future Work

Already verified in [49], [52], the technical module of the HTE model can successfully describe the behavior of a community's MG. This description is accurate and can predict either the exact power profile of the community's MG or the financial daily flows that mainly interest the community authorities. Actually, based on the maximization of the daily TB, the technical module exploits either the low-cost energy production of available ESS/DG/RES outputs or the financial energy arbitrage or the energy sale to the consumers [9], [17], [19], [32], [49], [52], [62], [63].

However, the application of the technical module requires sophisticated software packages or specialized personnel that discourage the communities since these issues critically deteriorate the community's budget. In order to promote a more tempting MG proposal for the communities, the main interest of this paper is to present a simplified but quasi-accurate method that can bypass either the costs for the licenses of the sophisticated MG software packages or the hiring of employees. The proposed economic module of the HTE model overrides the aforementioned financial obstacles presenting satisfactory immunity against various load consumption and RES power generation conditions that can occur during community's MG operation.

As it concerns the future work, the apparently positive correlation between PV generation profile and wind generation one is going to be examined on the basis of the technical module. Especially, if these profiles are indeed positively correlated, through the economic trade-off relations proposed by the HTE model, the RES diversification of investing only in one RES system with the lower cost is going to be investigated.

However, the main future research interest is going to focus on the economic module. Except for the simplified MG policies such as MG policy A and B, MG policy C offers the required system adaptability against the stochastic nature of the involved power consumption and power generation problems of the community's MG. First, further investigation is going to be made towards the trade-off between TB and allocation percentage. Adaptively adjusting the allocation percentage, a fixed TB can be achieved. A fixed cash flow can be a catching argument to the communities in order to install community's MGs. Second, the energy arbitrage may be further enhanced by exploiting the energy trade among power grid, ESS systems and consumers; through ESS farms, communities can strongly stimulate their local economies since they can consolidate for themselves the role of energy middleman between power grid and consumers. Third, despite the fact that MG policy C succeeds in offering a satisfactory

TB compromise and financial stability, there is a significant number of improvements to be made. These improvements are concentrated on the TB performance and on the algorithm and the code simplicity. More simplified MG policies are required so that their interpretation and compiling can be realized in open source platforms and various operating systems. Hence, future MG policies, which are based on the economic module and are going to be proposed, should avoid the heavy technical packages and special compilers. Fourth, the economic module should incorporate the DG and ESS operation in a way that allows the bypassing of technical module. Thus, the community's MG problem will transform from a technical issue into a techno-economic case.

Among the future fields of research, sophisticated technologies, new simulators, and operational strategies are emerging to help community's MGs mitigate load power consumption through energy efficiency improvements such as participation in demand response (DR) programs, peak load management initiatives, and the terminal scheduling/control via non-intrusive operations [88]-[91]. More specifically, recent efforts focus on making buildings "smarter" by adaptively controlling power consumption in areas such as lighting [92], electric heating, ventilation and air conditioning (HVAC) [93], [94] and information infrastructure [95] within buildings. Building smart offices [96], smart hospitals [97], [98] and smart universities [99], [100] is an emerging trend that encompasses Weiser's ubiquitous/pervasive computing concept [101] through the seamless integration of technologies [100]. Finally, the combined operation of community's MGs with other supported communications networks can also significantly improve the economic performance of MGs [102]-[107]. At the same time, the development of new ad-hoc power allocation algorithms and financial trade-off curves for community's MGs at a local and daily basis as well as their fairness and stability when various fluctuations occur in the MG surrounding environment define another two critical community's MG research topics [108]-[114].

VIII. Conclusions

In this paper, the potential of financially stimulating the local economies of communities, which suffer from the financial and economic crisis, through the installation of community's MGs has been examined. To assess the power and economic impact of community's MGs, the HTE model that consists of the technical and the economic module has been proposed.

Based on its well-validated technical module, the HTE model is able to accurately estimate the power production/consumption profile and the economic gains/costs/benefits of community's MGs. Then, based on the proposed economic module, the HTE model succeeds in quickly and accurately estimating the impact of load changes, RES power production changes and their combined presence on the power profile and cost-benefit analysis of community's MGs. Actually, the strong points of the HTE model derive from its newly proposed economic module; through its supported MG policies, the economic module permits: (i) the operation of community's MGs without additional costs regarding specialized personnel hiring; (ii) the bypassing of the mathematically complicated technical module; and (iii) the rapid, open-access and easy execution of its algorithm from non-specialist employees of the community.

Except for the aforementioned theoretical reports concerning the performance and practicability of the HTE model, a significant number of findings concerning the economic performance of community's MGs has been demonstrated, namely:

(i) During a typical day and in accordance with the baseline scenario, the daily TB of a community's MG can reach up to 8500$. Except for this high financial benefit, the proven financial stability is a critical factor regarding the promotion of MG concept to communities; (ii) The numerical results have validated that MG policies, which are supported by the economic module, preserves the financial stability of the community's MGs even if load consumption and RES power production changes range from -20% to 20%; (iii) Algorithmically simpler and more adaptive MG policies can be proposed using the economic module; (iv) Load changes have greater impact on the economic performance of community's MGs rather than RES power production changes; (v) Power changes of wind systems present higher TB impact on the economic performance of community's MGs in comparison with the respective ones of PV systems; and (vi) The economic module can be operational and can comfortably replace the technical module for load differences and RES power production differences that range from -47% to 26% and from -49% to 94% compared with the baseline scenario, respectively.

Finally, by applying the HTE model, community's MGs have been proven to be feasible technological solutions for stimulating local economies since they can define significant additional incomes for communities. Therefore, apart from the ecological awareness and great smart grid potential, communities obtain an efficient remedy against the financial consequences of the economic and financial crisis.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Trends in Renewable Energy
OPEN ACCESS **ISSN: 2376-2144**
Peer-Reviewed Review Article
futureenergysp.com/index.php/tre

Prospects for Bioethanol Production from Macroalgae

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Received September 19, 2015; Accepted October 10, 2015; Published October 11, 2015

Macroalgae (mainly marine macroalgae, *i.e.* seaweeds) are considered as a very promising source for bioethanol production, because they have high carbohydrate contents, superior productivity, and wide adaptability. Macroalgae are generally grouped into three major categories: red, green, and brown algae. Each category has thousands of species, and each species possesses its unique cellular structure, biochemistry, and constitutes. Converting macroalgae to bioethanol involves pretreatment, saccharification, fermentation, and distillation; and the establishment of economic pretreatment methods is always the first key step for bioethanol production. In present, dilute-acid or alkali hydrolysis is typically used to treat macroalgal biomass. Macroalgae can be depolymerized under mild conditions as they have low lignin content. The resulting polysaccharides can be converted to ethanol through enzymatic hydrolysis, followed by adding bacteria, such as *Saccharomyces cerevisiae* and recombinant *Escherichia coli* KO11. Compared with the separate hydrolysis and fermentation process, the simultaneous saccharification and fermentation process often provided higher ethanol titer and conversion efficiency. However, the research on bioethanol production from macroalgae is still in its early stage due to both technical and economic barriers, significant amount of research and development work is needed prior to the commercialization of bioethanol manufacture from macroalgae.

Keywords: Macroalgae; Bioethanol; Marine Macroalgae; Seaweeds; Pretreatment; Hydrolysis; Saccharification; Fermentation

1. Introduction

Bioethanol is a clean, safe, and bio-based energy, which is commonly regarded as one of the primary candidates to replace a fraction of liquid fossil fuels [1]. The importance of using bioethanol as a vehicle fuel is increasing domestic energy production, decreasing greenhouse gas emissions, and preventing environmental pollutions [2]. The global bioethanol production rose rapidly in recent years. Table 1 shows the production of bioethanol in different countries from year 2004 to 2014. The first generation bioethanol is mainly produced from sugars and starch-rich materials. The United States and Brazil are leaders in bioethanol production, making bioethanol from corn and sugarcane, respectively. In Europe and China, mainly cereals and sugars are used as the feedstock. As the development of fuels from biomass continues apace, the consumption of edible crops and sugars has raised food security, morality, and ethics issues [3].

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Tr Ren Energy, 2015, Vol.1, No.3, 185-197. doi:10.17737/tre.2015.1.3.0016

Table 1 Bioethanol production in different countries from 2004 to 2014 (million liters) (modified from [3])

Country	Major feedstock	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Argentina	sugarcane	174	157	205	225	315	416	442	455	469	483	498
Australia	sugarcane	-	27	63	100	156	238	384	387	389	392	395
Brazil	sugarcane	15,208	15,807	17,932	22,446	27,674	25,804	28,960	31,392	34,299	37,396	40,625
Canada	cereal	396	406	545	839	1083	1131	1573	1703	1714	1730	1721
China	cereal/sugarcane/ cassava	3673	3438	3509	3679	3964	4109	4368	4649	4824	4962	5121
EU-27	cereal/sugar beet	2576	2940	3701	3887	5021	5762	6465	7539	9155	10,79	11,774
India	sugarcane/wheat	1178	1120	1664	2082	2085	1680	1704	2430	2482	2532	2575
Indonesia	cassava	163	177	176	196	208	240	425	441	462	485	510
Japan	cereal	-	113	113	110	110	100	130	130	130	130	130
United State	corn	12,596	15,332	20,171	28,929	35,191	40,544	46,024	49,114	51,322	54,058	57,200

In order to overcome these issues, the second generation bioethanol, refined from lignocellulosic biomass, is developed to meet economic growth and morality requirements [4, 5]. However, the cultivation of terrestrial plants requires the resources that could be used for food production. In addition, due to the structural complexity of lignocellulosic biomass, the current conversion technologies including pretreatment, saccharification, fermentation, and separation of final products are relatively costly and low-yield [6]. Among all technical barriers, the delignification is often considered as the major obstacle, which must be combated before the commercialization of lignocellulosic bioethanol can become reality [7].

Recently, algae are viewed as the source of third-generation biofuels [8]. Generally, algae are grouped into microalgae and macroalgae, based on their morphology and size. This paper reviews the development of bioethanol production from marine macroalgae, since the production of freshwater macroalgae is not significant [9]. The words of macroalgae, marine macroalgae, and seaweed are used interchangeably within the context of this article. The major advantages offered by marine macroalgae over terrestrial plants are: (1) no competing with conventional agricultural plants for land, and utilization of different water sources (seawater, brackish water, and wastewater), (2) high area productivity, (3) non-dependence on agricultural input (fertilizer, pesticides, etc.), (4) being hydrolyzed easily into glucose as they contain lower lignin content in the cell wall [10, 11], and (5) easier harvesting as their plant-like characteristics [12]. All of those features enable macroalgae to become a very promising biofuel feedstock for the future.

2. Macroalgae Availability and Chemical Composition

Macroalgae, namely seaweeds, are conventionally classified into three major groups based on their photosynthetic pigments: red algae (*Rhodophyta*), green algae (*Chlorophyta*), and brown algae (*Phaeophyta*) [13]. The green algae can grow in all types of water environments. While red algae grow mainly in intertropical zones, and brown algae especially grow in tempered to cold or very cold waters [14]. Macroalgae can be mass-cultivated based on current farming technologies. Up-to-date, brown and red macroalgae are cultivated more than green species. The production of brown algae alone reached 15.8 million wet tons in 2010, which were harvested from both wild habitats and coastal farms [15]. At present macroalgae are grown for food production, fertilizers, and hydrocolloid extraction in Asia (mainly in China, Korea, Philippines, and Japan) accounting for about 72% of global annual production [16]. The macroalgae productivity ranged from 150 to 600 t/ha·y fresh weight [14], and the total worldwide production attains 19 million tonnes dry matter in 2014 [17]. The amount of the mass-cultivated macroalgae is six orders of magnitude greater than that of lignocellulosic biomass [18]. That implies that macroalgae could supply sufficient feedstocks for bioethanol production.

Macroalgae are significantly different from terrestrial plants in terms of their chemical compositions. Macroalgae have agar, carrageenan, laminarin, mannitoal, mannan, ulvan, fucoidin, and alginate, which are not available in lignocellulosic biomass [13, 18]. A summary of macroalgal divisions, compositions of their cell walls, and most significant characteristics is given in Table 2.

Table 2 Three macroalgae divisions and significant characteristics (modified from [19])

	Red algae	**Green algae**	**Brown algae**
Species	6000	4500	2000
Pigments	Chlorophyll *a* (*d* in some Florideophyceae); R- and C-phycocyanin; R- and B-phycoerythrin; allophycocyanin; α- and β-carotene and several xanthophylls	Chlorophyll *a*, *b*; α-, β- and γ -carotenes and several xanthophylls	Chlorophyll *a*,*c*; β-carotene and fucoxanthin and several other xanthophylls
Storage product	Floridean starch (amylopectin-like)	Starch (amylose and amylopectin)	Laminaran (β-1,3-glucopyranoside); Mannitol
Cell wall	Cellulose, xylans, several sulfated polysaccharides (galactans), alginate in corallinaceae	Cellulose (β-1,4-glucopyroside), Hydroxyproline glucosides; xylans and mannans	Cellulose, alginic acid, and sulfated mucopolysaccharides (fucoidan)
Representative	*Gracilaria spp.*	*Ulva fasciata*	*Laminaria spp.*
Carbohydrate (%wt)	76.7	43	60
Protein (%wt)	16.0	14.4	12
Lipid (%wt)	1.2	1.8	2
Ash (%wt)	6.1	16	26
Source	[20]	[10]	[21]

The pigment in red macroalgae is R-phycoerythrin, and their cell walls contain a small quantity of cellulose. Because the great majority of their components is gelatinous or amorphous sulfated galactan polymers, such as carageenan (up to 75% dry wt.), agar (up to 52%), and funoran, red macroalgae are also called as carrageenophytes and agarophytes [22]. Another distinctive feature for red algae is accumulating floridean starch and floridoside, which are similar to starch. But green and brown algae do not have these carbohydrates [23, 24].

The major photosynthetic product of green macroalgae is starch, and the cell walls of their outer and inner layers are predominantly cellulose and pectin, respectively. *Ulva spp.* and *Enteromorpha spp.* have 38-52% (dry wt.) of water-soluble ulvan and insoluble cellulose in the cell walls. Ulvan, the unique carbohydrates of green algae, is composed mainly of D-xylose, D-glucuronic acid, L-rhamnose, and sulfate [18].

Brown macroalgal cell walls are composed of cellulose, alginic acid, and other polysaccharides [19]. The accumulation product of this group are the carbohydrates of laminarin and mannitol [20]. Laminarin (*i.e.*, β-1,3-glucans) is a unique polysaccharide present in brown seaweeds [21]. Alginate accounts for up to 40% dry wt. as a principal material of the cell wall [14], and is composed of three different uronic acids: guluronic acid blocks, mannuronic acid blocks, and alternative blocks of mannuronic and guluronic units.

Macroalgae biomass is easier to be converted into simple sugars than land-plant biomass due to lack of lignin. Besides cellulose and hemicellulose, many algal species accumulate high content of starch as their food material. Carbohydrate contents of macroalgae vary widely by species and cultivar, representing 30-70%, 25-40%, and 30-50% of dry wt. for red, green, and brown algae, respectively [4, 18, 25]. Macroalgae species with high carbohydrate contents include: *Sargassum*, *Gracilaria*, *Euglena gracilis*, *Prymnesium parvum*, *Gelidium amansii* [26], and *Laminaria* [27]. Further species selection is still needed to develop strains with higher carbohydrate contents for use as the promising candidates for bioethanol production.

3. Bioethanol Conversion Processes from Macroalgae

In general, the steps for bioethanol production from biomass include pretreatment, enzymatic hydrolysis, fermentation, and distillation. Almost all kinds of macroalgae can be converted to bioethanol by decomposing their polysaccharides into simple sugars, followed by fermentation with suitable bacteria. However, the development of macroalgal conversion technology is still at an early stage, and the researches were conducted mainly on lab-scale.

Figure 1 shows the flow diagram of bioethanol conversion processes from macroalgae. Unlike the terrestrial biomass, macroalgae contain contaminants from the growth environment and unique chemicals, thus there are some differences in the bioethanol technological processes from other feedstock. The fresh algal biomass collected from the cultivation site need to be processed prior to bioethanol conversion steps [28]. The biomass can be washed with tap water to remove adhering salt, sand, epiphytes, and then sun-dried. Dry seaweed is more easily transported and stored. The granular dried seaweeds can be cooked with hot water and alkali or acid to extract the polysaccharides, or be directly extracted by using supercritical fluids. The extract may be purified and separated through filtration or centrifugation. Since macroalgae have various carbohydrates such as starch, cellulose, carrageenan, laminarin, mannitol, and agar, the saccharification of them is different from that of lignocellulosic biomass [13]. The hydrolysis of macroalgae commonly conducted by using dilute sulfuric acid and enzymes. And then bacteria, such as *Saccharomyces cerevisiae* (NCIM 3455 and ATCC 24858) and recombinant *Escherichia coli* KO11 (ATCC 55124), were added to the algae hydrolysates for ethanol fermentation. There are two methods for fermentation: one is the separate hydrolysis and fermentation process (SHF), and the other is the simultaneous saccharification and fermentation process (SSF). Bioethanol distillation in the lab is often carried out by using vacuum evaporation or small-scale distillation columns.

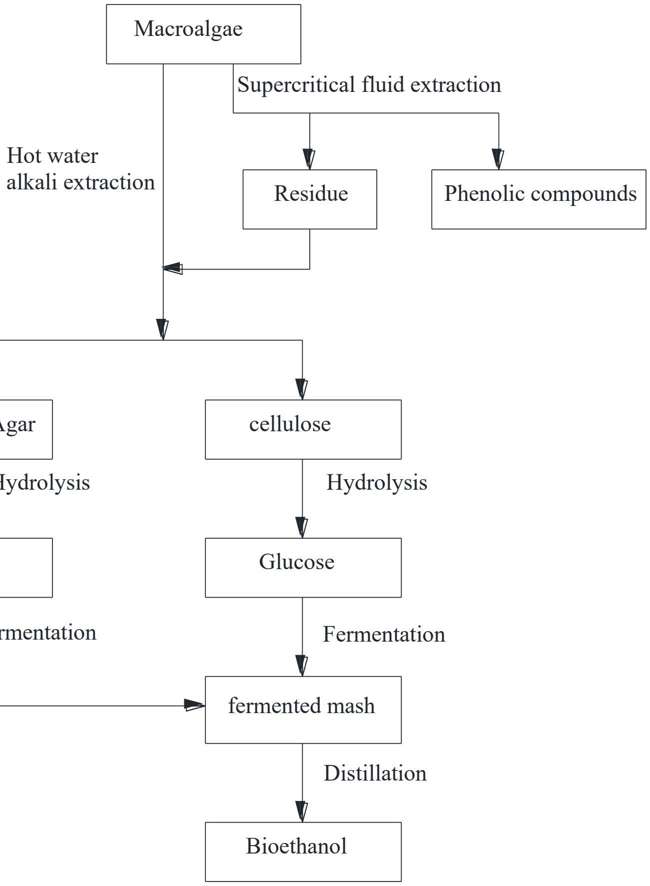

Figure 1. Block flow diagram of bioethanol conversion processes for macroalgae

4. Overview of Pretreatment Technologies for Macroalgae

The establishment of economic pretreatment methods is always the first key step for bioethanol production. The carbohydrate compositions of marine macroalgae highly depend on their species, which largely differ from those of terrestrial plants, so new efficient pretreatment methods are required to make the sugar monomers available for fermentation. Nowadays, although some physical, chemical, and biological pretreatments of macroalgae have been studied to increase the saccharification efficiency, those research activities looking for economically efficient technological solutions are in the early phase.

Different examples of bioethanol production and pretreatment technologies for macroalgae have been described in Table 3. Dilute-acid and alkali hydrolysis are typical physicochemical methods to treat raw macroalgal biomass [29, 30].

Table 3 Comparison of bioethanol yield from various seaweed feedstocks (Modified from [11]).

Algae	feedstock	Pretreatment	Sugar released (g/g biomass)	Ethanol yield (g/g sugar)	Ethanol (g/L)	Reference
E. cottonii	Residue after agar extraction	Solid acid + enzyme	0.814	-	14.1	[31]
Kappaphycus alverzii	Whole thallus	Acid	-	0.369	6.8	[32]
Kappaphycus alverzii	Whole biomass plus carrageenan granule	Acid	0.306	0.39	20.6	[30]
Gelidium amansii	Whole thallus	Acid+ enzyme	0.566	-	-	[23]
Gelidium amansii	Whole thallus	Dilute acid	0.422	0.38	27.6	[33]
Gelidium amansii	Whole thallus	autoclave+ enzyme	0.227	-	25.7	[34]
Gracilaria Salicornia	Two stage hydrolysis of fresh biomass	Acid+ enzyme	0.166	0.079	-	[35]
Gracilaria spp.	Whole thallus	Sequential acid + Enzyme	0.592	0.48	4.93	[20]
Gracilaria verrucosa	Pulp after agar extraction	Enzyme	0.87 g/g cellulose	0.43	-	[11]
Laminaria japonica	Whole thallus	Acid+ enzyme	0.376	0.41	23–29	[23]
Sargassum sagamianum	Whole thallus	Thermal liquefaction	-	0.386	1-2	[36]
Sargassum fulvellum	Whole thallus	Acid+ enzyme	0.096	-	-	[23]
Saccharina japonica	Whole thallus	Enzyme	0.614	0.41	37.8	[37]
Saccharina japonica	Whole thallus	Thermal acid	0.456	0.169	7.7	[38]
Ulva lactuca	Whole thallus	Acid+ enzyme	0.194	-	-	[23]
Ulva fasciata	Whole thallus	Hot buffer+ enzyme	0.205	0.45	-	[10]
Ulva fasciata	Whole thallus	Enzymatic	0.112	0.47	-	[39]
Zostera marina	Supercritical CO_2 extraction residue	Sulfuric acid + Enzyme	0.582	-	6.55	[40]

5 Ethanol Production from Marine Macroalgae

5.1 Red Macroalgae

Gelidium amansii, one of the most abundantly available red seaweed species, are known for high carbohydrate content. *G. amansii* predominantly consists of fibrin (cellulose) and agar (galactan) whose basic monomers are glucose and galactose, respectively [41]. The main products from dilute-acid hydrolysis of *G. amansii* are D-galactose, 3,6-anhydro-L-galactose (3,6-AHG), and D-glucose [42]. The galactose and glucose are classified as fermentable simple sugars, and the 3,6-AHG is non-fermentable. Since the physical morphology of agar is softer than that of cellulose, the hydrolyzed products of galactose and 3,6-AHG are released firstly under mild hydrolysis conditions. However, the 3,6-AHG, is also known as so acid-labile that it is very apt to be decomposed into 5-(Hydroxymethyl)furfural and, subsequently, into organic acids such as formic acid and levulinic acid, which act as inhibitors in the fermentation process [43].

It is well known that the fermentable sugar yields and the amount of inhibitors primarily depends on the three major factors: acid concentration, reaction temperature, and reaction time (or residence time for continuous process)[44]. A facile continuous method for dilute-acid hydrolysis of *Gelidium amansii* was developed to compare with the batch operation. The continuous acid pretreatment was done at a flow rate of 40 L/h, 15% (w/w) seaweed slurry containing 2% (w/w) of sulfuric acid at 150°C, and auto-generated pressure range of 3.0-3.5 bar. The product mixtures were continuously collected and the unreacted solid residual fibers were subsequently separated, followed by neutralization of hydrolysates by adding limestone ($CaCO_3$). The hydrolysate of *G. amansii* was then fermented by *Brettanomyces custersii* KCTC 18154P. Results showed the hydrolysate obtained from the continuous process attained a high sugar concentration with low quantity of inhibitors, thereby leading to the higher ethanol yield (the final ethanol titer of 27.6 g/L after 39 h), than that of the batch reactor (11.8 g/L after 56 h) [33].

In order to produce a high quality hydrolysate with minimal inhibitors, sequential acid and enzyme hydrolysis of *Gracilaria spp.* was studied. The dilute-sulfuric acid hydrolysis process was carried out by using 2% (w/v) of dried *Gracilaria spp.*, and optimized at 121℃ via varying acid concentrations (0.025-0.25 mol/L) and residence time (up to 60 min). The hydrolysates were adjusted to various pHs (pH 2–8) at the end of the acid treatment. After pH adjustment, the enzymatic hydrolysis was performed with various amounts of cellulase (0.01- 8% w/v) at 50°C for 6 h. The *Gracilaria* hydrolysate was fermented in batch and repeated batch modes by using immobilized *S. cerevisiae* Wu-2 cells. The process maximally released 11.85 g/L of glucose and galactose, yielding 4.72 g/L of ethanol at the rate of 0.48 g/g sugar-consumed with a 94% conversion efficiency [20].

For converting red macroalga *Gelidium amansii* (GA), GA was autoclaved at 121°C for 60 min to reduce the galactan content. After the autoclave treatment, 177 g glucose and 50 g galactose were produced from 1 kg GA. Enzymatic hydrolysis was conducted with a cocktail of cellulase (Celluclast ® 1.5 L) and β-glucosidase (Novozyme 188). SHF (2% substrate loading, w/v) produced a maximum ethanol concentration of 3.33 g/L and an ethanol conversion yield of 74.7% after 6 h. In contrast, SSF achieved an ethanol concentration of 3.78 g/L and an ethanol conversion yield of 84.9% after 12 h. With an increased biomass concentration, the ethanol concentration of 25.7 g/L was attained from 15% (w/v) treated biomass after 24 h SSF processing [34]. The results indicated that autoclaving can increase the sugar yields and ethanol conversion yield of GA, and also showed that SSF is superior to SHF for ethanol production.

Carrageenan is the major polysaccharide constituent of red algae, which consists of repeating of β(1-3)-D-galactose and α(1-4)-3,6-anhydro-D-galactose [41]. Purified carrageenan is generally used for forming thick solution or gel [22]. During manufacturing carrageenan, seaweeds were treated with alkali solution (1-10% NaOH or KOH) at 80°C for 0.5-5h, resulting in 60-70% solid residues (SWBC) with high carbohydrates content. One study used this stream of seaweed wastes as the bioethanol feedstock [45]. Researchers treated seaweed wastes with peracetic acid (PAA) followed by different types of ionic liquids (ILs): 1-ethyl-3-methylimidazole acetate ([Emim][OAc]), 1-hexylpyridinium chloride ([Hpy][Cl]), and 1-ethyl-3-methylimidazolium diethylphosphate ([Emim][DEP]). For a 48-hour saccharification, the cellulose conversions of untreated and pretreated seaweed wastes with PAA followed by [Emim][OAc], [Hpy][Cl], and [Emim][DEP] were 77, 62, 91, and 84%, respectively. The untreated SWBC had a high cellulose conversion, which may be caused by the alkali pretreatment or low lignin and hemicellulose contents of this seaweed. Meanwhile, PAA-IL pretreatments did produce more amorphous cellulose structures, which are beneficial to cellulose conversion [46].

5.2 Green Macroalgae

The most common green macroalga, *Ulva prolifera* (UP), contains about 62% carbohydrates, 27% protein, 0.3% lipid, and 11% ash of dry matter [47]. However, the carbohydrates of *U. prolifera* are chiefly in the form of complex hydrocolloid ulvan, which shows very high viscosity by undergoing a random coil to double helix transition while cooling [48]. The high viscosity of ulvan is one reason that hindered the high production of bioethanol from this species. The depolymerase produced by *Catenovulum* *spp.* LP, showed high efficiency and high specificity to UP for monomer sugar production. During the enzymatic hydrolysis, the viscosity of 1.2% UP solution obviously declined from initially 1127 to 7.2 mPa·s within 95 min. Reducing sugar yield attained 50.2% in 6 h at the optimal conditions of pH 6.0 and 35°C [49]. Compared to the commercial enzymes, this depolymerase might bring promising prospects for bioethanol production from *U. prolifera* biomass.

Chaetomorpha linum, one of green macroalgae species, has rigid epidermal cell walls consisting of highly crystalline cellulose [35]. The cellulose content (35-40%) of *C. linum* is higher than that of other algae, and similar to that of land-based biomass. For breaking down the cellulosic structure of *C. linum*, following five pretreatment methods have been employed: steam explosion (STEX), hydrothermal pretreatment (HTT), plasma-assisted pretreatment (PAP), wet oxidation (WO), and ball milling (BM) [50]. HTT and WO were performed with 4% *C. linum* at 200°C; *C. linum* (35%) was treated by STEX at 200-210°C for 5 min; the PAP treatment was performed with raw material (50%) for 20-60 min with 1% ozone gas flow rate of 0.01 L/s; and the BM experiment was carried out for 18 h at 180 rpm. WO, HTT, PAP, BM, and STEX resulted in glucan concentrations of 74, 60, 46, 38, 36 g/100 g dry matter, respectively. Using a SSF process with the commercial cellulase enzymes (Celluclast 1.5 L and Novozyme 188) and *S. cerevisiae* ATCC 96581 for ethanol fermentation, WO and BM showed the highest ethanol yield of 77.2% of the theoretical ethanol yield. However during WO, about 50% of the biomass (especially C5 sugars) was lost. The results suggested that physical pretreatment method like BM is already effective enough to break down the cellulosic structure of *C. linum*.

5.3 Brown Macroalgae

Conversion of *Sargassum spp.*, a brown seaweed species, was conducted by using dilute acid hydrolysis and SHF [51]. In terms of glucose and other reducing sugar yields, the optimal pretreatment condition was found to be (3.4-4.6%w/v H_2SO_4, 115°C and 1.50 h). The residue after pretreatment was hydrolyzed with cellulase (*Trichoderma reeseii* ATCC 26921) and β-glucosidase, and then fermented by *S. cerevisiae* for 48 h. The ethanol conversion rate achieved 89%, which was obviously higher than the theoretical yield of 51% based on glucose as substrate. Since all glucose was consumed during fermentation, other sugar sources might be present in the hydrolysate.

Zostera marina is a source of natural antioxidants in the food and pharmaceutical industries. After washing, drying, grinding, and sieving, antioxidants (phenolic compounds) were extracted by using supercritical CO_2 from this brown alga. The contents of lignin, hemicellulose, and α-cellulose in the residues were 22.4%, 16.89%, and 27.39%, respectively. Because supercritical fluid extraction already loosen the lignin structure [40], the raffinate phase would either be directly used for SSF or hydrolyzed by enzyme/dilute acid. Under optimized conditions, a reducing sugar yield of 58.24 g/100 g dry-feed was reached by consecutive enzymatic and acid hydrolysis with a commercial cellulase (Cellic CTec2).

6 Prospect on the Utilization of Macroalgae for Biofuels Production

As an abundant and carbon-neutral renewable resource, macroalgae represent an unrealized feedstock that might expand existing bioethanol industries. Currently, macroalgae are gaining more attention because of their plant-like characteristics, fast growth rate, superior productivity, lower energy inputs, and no land requirements. In terms of availability, the annual production of brown algae was 9.72 million tons (dry weight) in 2004, representing the largest seaweed source; and red algae produced 3.99 million tons of dry biomass at the second place [52]. Another advantage of macroalgae is high content of carbohydrates (cellulose and hemicellulose) and the paucity of lignin resistant [53]. Although, the notion of macroalgae-based bioethanol production is environmentally better than the fossil fuels, but still suffer from low cost effectiveness and technological barriers [14]. The industrial-scale technologies for seaweed conversion still require significant basic research and development.

Since the price of a final product is directly related to the cost of feedstock, the price of seaweed is an important factor in the economics of a bioethanol process. The estimated macroalgal bioethanol production cost is ca. $0.50/kg (dw) ($0.16 from corn) [54]. Algae production cost is connected with the available technologies for cultivation, harvesting, and processing. Although macroalgae can be cultivated both naturally and artificially, approximately 90% of total feedstock were currently harvested from cultivated sources [21]. The production cost will decrease with the increase of macroalgae yield per unit area. To date, there are limited numbers of economic assessments on seaweed-based bioethanol technologies, as the research just started. Although it is impossible to make full-scale and periodically life cycle assessment right now, the processing technologies for bioethanol production from macroalgae should be estimated not only from the viewpoints of technical feasibility and economic efficiency, but also from the environmentally friendly point and the recycling of byproducts.

ACKNOWLEDGMENTS

The authors are thankful for the financial support from the Major program for Science and Technology Development of Henan Province, China (No. 132102310042), and the crosswise project of Henan Tianguan Biofuel Eng. Co. Ltd., China. (No. 211500532704).

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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