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A model for an economic evaluation of energy systems using TRNSYS

Manuel Villa-Arrieta[a,*], Andreas Sumper[b]

[a] *Escola Tècnica Superior d'Enginyeria Industrial de Barcelona (ETSEIB), Universitat Politècnica de Catalunya (UPC), Av. Diagonal, 647. 08028 Barcelona, Spain*

[b] *Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Universitat Politècnica de Catalunya (UPC), Av. Diagonal, 647, Pl. 2. 08028 Barcelona, Spain*

Abstract

This paper presents a technical-economic model for the evaluation of energy systems called Energy Assessment Tool of Energy Projects (EATEP). It was created with the TRaNsient System Simulation Tool (TRNSYS) and works in parallel to the technical simulations in this software. The EATEP links, in hourly time steps, technical and economic variables that can determine the functioning of energy systems and the profitability of the investment required for their implementation. The economic calculation procedure, as described in the European standard EN 15459:2007, of the Energy Performance of Buildings Directive (EPBD) of the European Commission, has been adapted to the characteristics of TRNSYS to develop the calculation methodology of the EATEP. The final use of this resulting tool is the evaluation of the energy self-consumption of communities from the technical-economic point of view, analyzing the investment in distributed generation systems by consumers, prosumers and energy producers. The operation of the EATEP has been validated through two cases that demonstrate the wide range of its applicability and versatility. In the first case, the calculation of indicators identifies the best alternative among various investment options in the evaluation of self-consumption energy systems. The second case, evaluates systems in which producers, consumers and prosumers exchange energy and economic flows; the tool calculates indicators of costs, revenue and income (the margin between revenue and costs).

Keywords: Technical-economic evaluation model; Energy Performance of Buildings Directive; TRNSYS; Distributed generation; Net-Zero Energy Communities

1. Introduction

The economic evaluation procedure regularly used in feasibility studies of energy systems, is carried out in *series* to the technical evaluations of its operation, as in the case of [1–14]. In

* Corresponding author. E-mail address: manuel.ricardo.villa@estudiant.upc.edu

other words, the economic evaluation of this type of systems is carried out after obtaining the consumption/generation/storage/energy saving data in technical simulations. This can limit the dynamic link that may exist between the technical, economic, and financial variables that determine the hourly performance of energy systems, i.e. when evaluating energy systems made up of consumption facilities and generation facilities. Another limitation in these feasibility studies of energy systems, is the difference in the terminology of economic and financial indicators calculated in energy generation projects and projects to reduce energy consumption. In this paper, we present an economic evaluation model built into the TRaNsient System Simulation Tool (TRNSYS) that serves as a tool that covers these limitations and also presents another series of novelties. This tool, called Economic Assessment Tool of Energy Projects (EATEP), permits the economic evaluation of the energy systems in parallel to their technical evaluation. In this way, the EATEP considers the effect of technological and environmental costs and the hourly variation of energy prices on the technical performance of energy systems and profitability of their investment. Likewise, the tool economically evaluates the energy exchanges between distributed generation systems (DG) [15] and centralized generation systems.

The economic calculation procedure of the EATEP is an adaptation of the European standard EN 15459:2007 [16] to operate with TRNSYS. This standard reflects the economic calculation procedure of the Energy Performance of Buildings Directive (EPBD), which is the main European legislative instrument for the promotion of buildings with close to zero energy consumption. The EATEP extends the scale of application of EN 15459:2007; which allows for the evaluation of net zero energy consumption, known as Net-Zero Energy Building (NZEB) and Net-Zero Energy Community (NZEC), in buildings and communities, and similarly with energy surpluses, known as Net-Plus Energy (NZEB) and Net-Plus Energy Community (NZEC). In addition, it broadens the focus of this standard: along with energy consumption systems, it also allows for the economic evaluation of the viability of investment in centralized and DG systems. On this basis, the tool can calculate indicators, equivalent to those proposed in the EPBD, but designed to analyse the current value of revenues and incomes from the sale of CO_2 emission rights. The result is a model that can calculate a wide variety of economic-energetic, economic-environmental, and economic-energetic-environmental indicators, in order to identify the best alternative within a group of investment options.

This model is thus proposed as a tool in TRNSYS to analyse, i.e., the profitability of the investment required by consumers, prosumers, and energy producers, in the process of energy transition in communities towards the use of their local energy resources through the development of the DG.

The following details the novelties presented by the model with the use of EPBD (EN 15459:2007) and TRNSYS.

1.1. Use of the EPBD in the design of the EATEP

The European standard EN 15459:2007 normalizes the economic calculation procedure of the EPBD, which is the legislative instrument developed in the European Directive 2010/31/EU [17] and supplemented by Delegated Regulation (EU) No. 244/2012 [18]. The objective of the EPBD is to establish a common framework to assess the energy performance of buildings. Its economic calculation procedure is an analysis of the expected costs during the useful life of the energy systems. It includes the calculation of the Global Cost (CG), as the current value of the costs, and the comparative analysis called Cost-Optimal. The latter classifies the CG according to the primary energy consumed by each evaluated investment alternative[19]. The application of these indicators is highlighted in the economic evaluation of NZEB [20–22] and the study and development of NZEC [23] and Smart Cities [24]. In the EATEP, the CG and Cost-Optimal indicators are both used in the analysis of the investment in Energy Efficiency Measures (EEMs) in NZEB, NPEB, NZEB and NPEC. Indicators equivalent to these are proposed here, but are designed to analyse, within the same evaluation framework, the investment in energy generation systems. The new indicators are Global Income (IG), used to calculate the present net value of revenues and the margin between Revenues and Costs (ISC) used to calculate the present net value of the margin between IG and CG. A comparative analysis indicator has also been designed to classify the ISC according to the amount of energy, in terms of primary energy, that can be exported by each of the investment alternatives considered in the evaluation of energy generation systems. Finally, on this same basis of calculation, financial indicators proposed by the National Renewable Energy Laboratory (NREL) [25] and the Effect-Cost-Index [26], have been adapted.

1.2. Use of TRNSYS in the development of the EATEP

The EATEP was created using the dynamic simulation software of energy systems, TRNSYS. This software has been used because of the technical advantages it has in the expansion of the scale and focus of the application of the indicators proposed in the EPBD. TRNSYS is a complete and expandable simulation environment for the simulation of systems. Its operation is based on the interconnection of subroutines, called Types, fed by variables, known as Inputs and Parameters, which are processed to deliver Outputs as results. During the simulation, Inputs vary, Parameters remain constant, and Outputs become Inputs of other Types. Although there is a wide variety of models and software available for the technical-economic simulation of energy systems [27] with different purposes and approaches, including specific methodologies on renewable energies [28] and DG [29], TRNSYS allows: 1) to evaluate different types of renewable energy systems, as in the case of [9–11,30,31]; 2) to customize and add subroutines [32] to simulate new technologies, as in the case of [8,33], and to develop technical-economic models of energy systems, as in the case of [34]; and 3) to link its operation with that of other simulation software, as in the case of [12,13]. TRNSYS has in its library two Types to perform economic calculations, Type 19 and the Type 580. Neither of these two models has the characteristics proposed in the EATEP. The first one is only applicable to the analysis of the life-cycle cost of a solar powered system, comparing capital and back-up fuel costs to the fuel costs of a conventional non-solar powered system [35]. The second, is similar to Type 19, uses the P1 and P2 methods described by Brandemuehl and Beckman, and Duffie and Beckman, [36].

The operation of the EATEP is described below in section 2, its validation in section 3, and finally, sections 4 and 5 provide discussions and conclusions.

2. Description of the operation of the EATEP

EATEP, working in parallel in hourly time steps with the simulation of the energy systems in TRNSYS, seeks to determine Annual and Global results, to later calculate a group of indicators, called Comparative Indicators, with which it is possible to identify the best alternative within a group of investment options, called Packages. The Annual results are the sum in each year *t* of the evaluation period T, of energy, environmental and economic values, and the Global results are the sum of each of these groups of annual results. The economic results are delivered in terms of the current value of the cash flows expected in each year. Each Package is a set of EEMs and/or energy technologies, called Components. The Packages are numbered from 1 to p, number 1 being the reference case against which the other evaluated packages are compared. The energy systems that are feasible to evaluate with the EATEP are grouped into the following three categories of energy projects:

1. Energy Efficiency Projects (EEP): projects at final energy consumption points in which the investment in EEMs and/or self-consumption technologies seek to reduce energy consumption and/or reduce the consumption of external energy resources and their associated costs. It includes projects carried out by Consumers or Prosumers, in buildings and communities, and projects of Smart Grids [37].
2. Energy Generation Projects (EGP): projects at energy generation facilities carried out by Producers in which the investment in energy generation technology systems and/or EEMs seek to reduce energy consumption and/or increase energy export to increase the margin between revenues and costs.
3. EEP-EGP projects: projects in which EEP and EGP energy systems are jointly evaluated in the same economic scenario. The EGPs are evaluated as systems supplying energy for the EEP systems. This includes NZECs of DG systems evaluated independently as EEPs and EGPs.

Fig. 1 presents the operating diagram of the EATEP. Boxes 1, 2 and 3 represent the calculation process in the evaluated Packages, and Box 4 the calculation of Comparative Indicators. Box 1 details the Parameters and Inputs (data that vary in hourly time steps) that feed the EATEP during the evaluation period, in order to obtain the annual and global results (Outputs). Parameters are configuration data, such as the value of T among others; Inputs are energy data, economic and financial data, primary energy conversion factors and CO_2 emissions, and evolution rates used when Inputs are entered as a fixed value. Comparative Indicators are divided into subgroups of indicators called Benefits, Financial, Effect-Index and Economic-Optimum (described in section 2.2.4), their calculation procedures vary between EEP and EGP. The first to be performed, and from which the other subgroups are calculated, is the Benefits Indicators, this calculation is derived from the difference between the objective of the two project categories. Table 1 summarizes this difference.

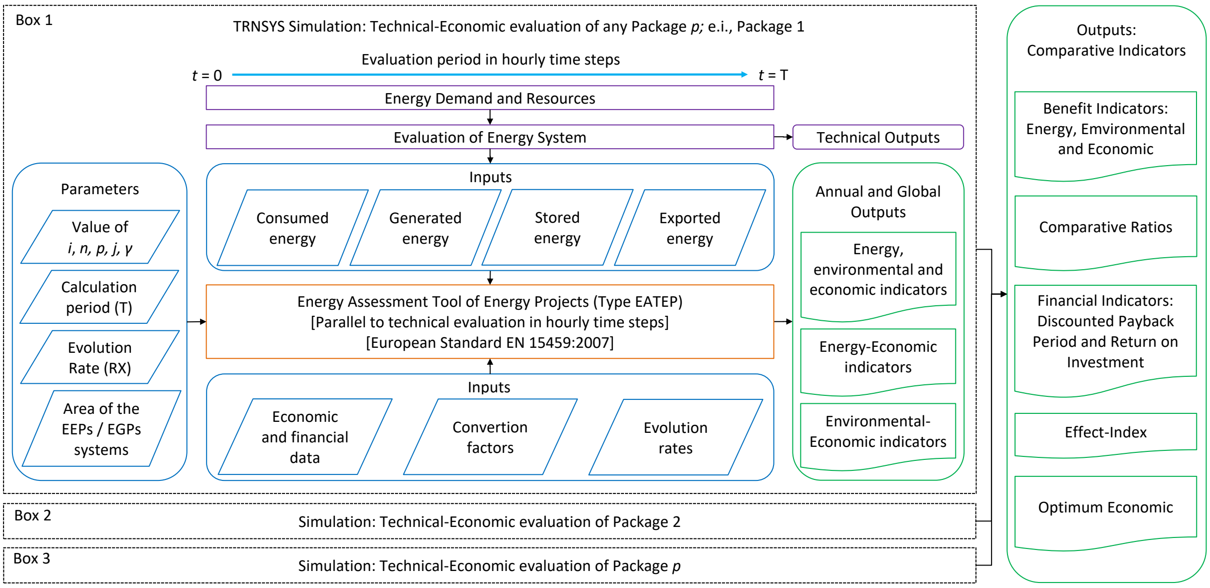

Fig. 1. General diagram of the calculation process of the EATEP.

	Energy Efficiency Project (EEP) (*)	Energy Generation Project (EGP)
Energy Benefit	Reduction of energy consumed	Increase of energy exported
Environmental Benefit	Reduction of CO_2 emissions produced by energy consumed	Reduction of CO_2 emissions produced by energy exported
Economic Benefit	Reduction of costs (**)	Increase of income (margin between revenue and costs)

Table 1. Description of the evaluation of Benefits Indicators in EEP and EGP. (*) The Benefits on the evaluation of EEP equals savings: economic savings, energy savings and environmental savings. (**) The Revenues in EEP are counted as negative costs to help reduce Costs.

The three categories of energy projects can be evaluated in the following five configurations (Fig. 2 describe them graphically):

I. The evaluation of an EEP made up of a quantity *p* of Packages, and these latter of quantity *j* of Components.

II. The evaluation of an EGP made up of a quantity *p* of Packages, and these latter of a quantity *j* of Components.

III. The evaluation of a Total Energy Efficiency Project (TEEP) that group the results a quantity *i* of EEPs, where all evaluate the same Packages.

IV. The evaluation of a Total Energy Generation Project (TEGP) that group the results a quantity *n* of EGPs, where all evaluate the same Packages.

V. The joint evaluation of a TEEP and a TEGP, or an EEP and an EGP, assuming that a quantity *n* of EGPs supplies part of the energy demand of a quantity *i* of EEPs. EGPs results are obtained based on the results of EEPs.

I EEP { (Packages $1, 2 \ \ldots, p$)

II EGP { (Packages $1, 2 \ \ldots, p$)

III TEGP { (EGP $1, 2 \ \ldots, i$) { (Packages $1, 2 \ \ldots, p$)

IV TEGP { (EGP $1, 2 \ \ldots, n$) { (Packages $1, 2 \ \ldots, p$)

V TEEP-TEGP $\begin{cases} \text{TEEP \{ (EEP } 1, 2 \ \ldots, i) \\ \text{TEGP \{ (EGP } 1, 2 \ \ldots, n) \end{cases}$ { (Packages $1, 2 \ \ldots, p$)

Fig. 2. Representation of the organization of the Packages in each of the evaluation configurations of the EATEP.

2.1. Development of the Types EATEP

The EATEP consists of two Types, the EATEP-EEP and the EATEP-EGP, developed to evaluate the systems of EEP and EGP respectively. The variables, Parameters and Inputs, used in these two subroutines are described below.

2.1.1. Parameters and Inputs

In the two Types, the Parameters (Table 2) include information on how the evaluations were prepared, the area of the systems and variables to indicate the value of the evolution rates of the Inputs (energy and economic data) entered as fixed values. The Inputs (Table 3) include variables that can be entered as a fixed value or as a value generated in another Type. Inputs of economic character, and consequently the related Outputs, can be of any monetary unit; here the Euro unit (€ or EUR) is used due to the characteristics of the cases with which the EATEP was validated.

Parameter, symbol and unit	Definitions
Number of elements used	*i*: EEPs; *n*: EGPs; *p*: Packages, where *p* = 1 is RC; *j*: Components; *γ*: energy vectors.
Calculation period (T)	Time period used for the calculation.
Evolution Rate (RX) [%]	Annual variation rate of all Inputs, where *X* represents the Input symbol.
Area (A) [m²]	Area of the facilities in which the energy project is evaluated.

Table 2. Definition of Parameters used in the EATEP according to the chosen calculation procedure and the characteristics of TRNSYS. Source: Adapted from [16].

Input, symbol and unit	Definitions
Consumed Energy in EEP (EC_γ) [Wh]	Hourly data of the final energy consumed to cover the energy demand in the EEP evaluation. Sum of energy consumption from local and external energy resources.
Exported Energy in EEP (EP_γ) [Wh]	Hourly data of the energy surplus in EEP. Their calculated economic value is accounted for as a negative cost that helps reduce total energy costs

Exported Energy in EGP (EP_γ) [Wh]	Hourly data of energy exported in EGP. Their calculated economic value is a revenue by energy sold.
Generated Energy (EG_γ) [Wh]	Hourly data of energy generated in EEP and EGP.
Stored Energy (ES_γ) [Wh]	Hourly data of stored energy in EEP and EGP.
Lifespan (Tn_j) [Years]	Life expectancy for a Component *j*.
Cycle Use (U_j) [Times)	Number of times per hour that a Component *j* is used. Can be used to specify a number of loads and discharges of an energy storage system before being replaced.
Tax [%]	Annual percentage value (0 < Tax < 100) to include taxes to the fixed and variable terms of the calculation of the energy costs.
CO_2 Factor (FCO2_γ) [Wh/CO2]	Conversion factor of the amount of CO_2 produced by each unit of energy generated. In the evaluation of EEP can be used as a value of hourly variation in energy consumption to calculate the amount of CO_2 emissions in an energy mix.
Primary energy conversion factor (FPE_γ) [Wh_PE/Wh]	Primary energy conversion factor of each energy vector *γ*
CO_2 Emissions Cap (CAP) [tCO2]	CO_2 emissions limit granted annually in EGP.
Market interest rate (R) [%]	Interest rate agreed by lender (0 < R <100).
Inflation rate (Ri) [%]	Specific evolution rate to calculate the Annual depreciation of the currency (0 < Ri < 100).
Component Costs (CC_j) [€]	The final cost of an energy component or system *j* in the market.
Added Costs (AdC_j) [€]	Costs whose accounting period can be less than period T, and which can be included in a specific group of costs: to Components costs (AdCC), as positive cost to account for a tax or fixed charge, etc., or a negative cost to include a subvention; to the access costs of energy networks (AdCAE), AdCAEC to energy consumption and AdCAEP to energy exports.
Costs of Access to Energy Grids (CAE_γ) [€]	Fixed toll for access to energy distribution networks: CAEC to apply these costs to energy consumption and CAEP to energy exports.
Price per Energy Unit (PEU_γ) [€]	Hourly price in the market for each unit of energy.
Added Revenue (AdI_γ) [€]	Revenue can include additional vale, as a fixed value not dependent on the exported energy or CO_2 emissions.
Carbon Credit Price (PCO2) [€]	Generic term representing the right to emit one tonne of carbon dioxide or the mass of another greenhouse gas with a carbon dioxide equivalent (tCO_2) equivalent to one tonne of carbon dioxide.

Table 3. Definition of Inputs used in the EATEP according to the chosen calculation procedure and the characteristics of TRNSYS. Source: Adapted from [16].

2.1.2. Outputs

The Outputs (Table 4) report the results of the economic evaluation. They are divided into energy, environmental and economic indicators, delivered in annual and global quantities. Among these, the economic results are delivered as current values (referred to the initial year of the evaluation).

No., Output, symbol and unit	Definitions
1. Discount rate (Rd) [-]	The discount rate is a definite value to compare the monetary value in a different period.
2. Energy results [Wh; Wh_PE]	Each of the Inputs that feed the EATEP are delivered as Outputs: 2.1. EC_j. 2.2. EP_j. 2.3. EG_j. 2.4. ES_j.
2.5. Energy Balance (EB) [Wh; Wh_PE]	Margin between the energy exported and the energy consumed.
Economic results	Economic flows presented in annual and global values in terms of current value.
3. Cost [€]	Negative economic flow that accounts for four cost groups: investment, running, energy and environmental.
3.1. Investment Costs (CI_j) [€]	Includes the costs for the purchase of Components *j* in year 0 (Initial Investment Costs), its replacement in any year of the calculation period, and its value (*VF_j*) at the end of this period.
3.1.1. Initial Investment Costs (CII_j) [€]	Costs incurred in the purchase of Components in year 0 of the calculation period.
3.1.2. Total Replacement Costs (CRT_j) [€]	Includes the Replacement Cost and Disposal Costs of the Component or energy system *j* once its lifetime has expired or when it completes its cycles of use.

3.1.2.1. Replacement Costs (CRM_j) [€]	Replacement Cost of Component or energy system *j*.
3.1.2.2. Disposal Costs (CD_j) [€]	Costs incurred in the elimination of the Components or energy systems j, executed in its replacement.
3.1.3. Final value of Components (VF_j) [€]	The final value corresponds to the value of the Component *j* at the end of the calculation period. This value is compared with the initial investment at the time of installation.
3.2. Running Costs (CR_j) [€]	Running Costs includes maintenance cost and an Added Cost.
3.2.1. Maintenance Cost (CM_j) [€]	Costs of measures for preserving and restoring the desired quality of the facility. This includes annual costs for inspection, cleaning, adjustments, repairs under preventive maintenance, consumable items.
3.3. Energy Costs (CE_j) [€]	Includes Energy Costs by Energy Consumption, CEC, in EEP and EGP evaluation, and Energy Costs by Energy Exported, CEP, in the EEP evaluation.
3.3.1. Variable Energy Cost (VCEC_γ) [€]	Part of the energy cost that is calculated based on energy consumption.
3.3.2. Fixed Energy Cost (FCECG_γ) [€]	Part of the energy cost that accounts for the cost of access to distribution networks or energy transport.
3.4. Environmental Costs (CV_j) [€]	Costs for the emission of polluting gases in terms of tonnes of CO_2 calculated from the market price of the CO_2 emission right.
3.5. Average Annual Cost (CAA) [€]	Arithmetic average of the Global Cost in the evaluation period.
4. Revenue [€]	Positive economic flow that accounts for the value of the energy exported and the CO_2 emission rights sold. Only applicable in the evaluation of EGPs.
4.1. Revenues by Energy (IE_γ) [€]	Revenues received from the sale of energy in the EGP evaluation.
4.2. Revenue by sales of carbon credit (ICO2) [€]	Income received from the sale of CO_2 emission rights in the EGP evaluation.
4.3. Added Revenue (AdI_γ) [€]	Additional revenue.
5. Income (ISC) [€]	Indicator of the margin between the Revenues received and the Costs incurred. This indicator does not refer to the financial indicators Net-profit (= Pre-tax profit − tax) or Gross profit (= sales revenue − cost of sales and other direct costs) since the model does not include the discount of financial taxes, and costs include operational costs and investment costs (as is used in the EPBD).

Table 4. Definition of Outputs used in the EATEP according to the chosen calculation procedure and the characteristics of TRNSYS. Source: Adapted from [16].

2.2. Example of the evaluation of an EEP-EGP project

Fig. 3 shows an example of the evaluation of an EEP-EGP project. This graph describes the operational relationships between the Types EATEP-EEP and EATEP-EGP and the Types that could represent local energy resources, the energy demand of EEP(*i*) and the energy systems of EEP(*i*) and EGP (n). (1) indicates that this energy demand is covered with self-generated energy and with energy imported from the outside by means of Output Consumed Energy; and (2) indicates that these local energy resources feed the self-generation system. The dotted line box indicates the evaluation of the EGP(*n*) as an external energy resource of the EEP(*i*). Apart from the energy exported by the EGP(*n*) the Type EATEP-EGP and all its group of annual and global Outputs is also calculated.

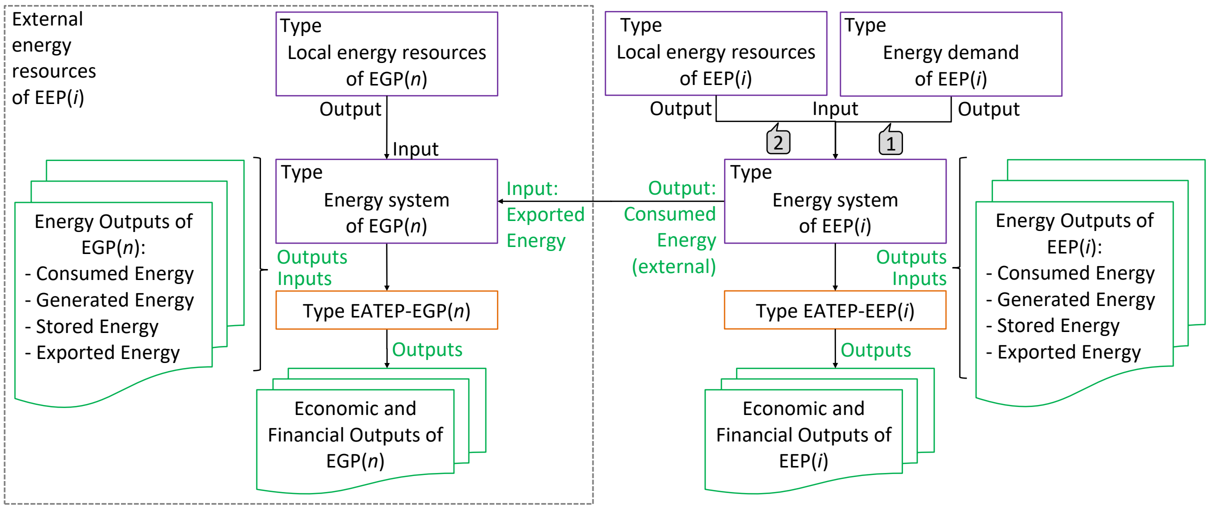

Fig. 3. Representation of configuration V in the TRNSYS.

2.3. Economic calculation procedure

2.3.1. Structure of economic flows

Fig. 4 presents the structures of the economic flows that allow for the calculation of the economic gain. Unlike the costs groups, the revenue and income are only applicable in the EGP evaluation.

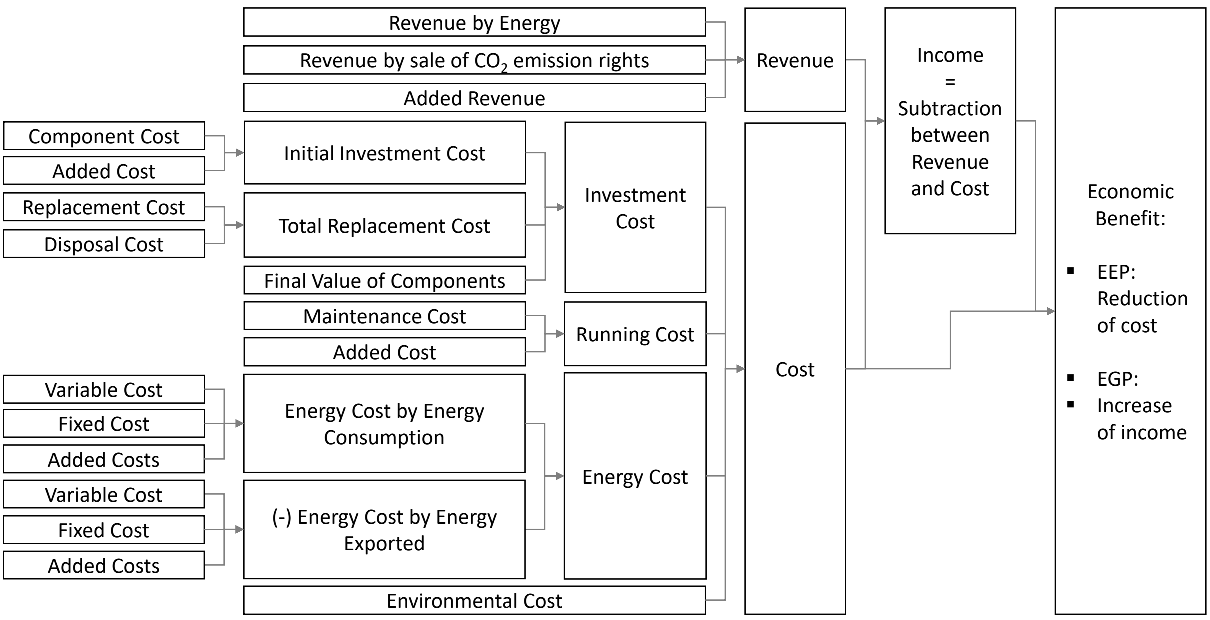

Fig. 4. Structure of the groups of economic flows calculated in the EATEP. Source: Adapted from [16]. Note: Revenue and Income are only applicable in the evaluation of EGP.

2.3.2. Calculation of economic flows

Calculation of the Global Cost proposed in the EPBD

The Eq. (1) [16] is the equation originally proposed in the EBPD to calculate the Global Cost. Where, T is the period of economic evaluation; *t* is each year of T; *CI* is the Initial Investment Costs; *Ca* is the Annual Cost or the sum of the energy costs, the Costs of CO_2 emissions, the Replacement Cost of Components and Maintenance Cost; *Rd* is the Discount Rate at which the economic values are updated to the initial year (t = 0); and *VF* is the final value of the year T of the Components. The Rd, Eq. (2), depends on the Real Interest Rate (RR), Eq. (3), that is calculated according of the Inflation Rate (RI) and the Market Interest rate (R). Finally, the Eq. (4) [16] is used to calculate the VF. In this equation the first two factors represent the last Replacement Cost (at the year of its replacement) in which *VI_j* is the initial value of Component *j* and *RX_j* is the evolution rate of its price. *n_T (j)* is the total number of component replacements over the calculation period, and the penultimate factor represents the depreciation line of the last replacement cost of the last component replacement divided by its lifespan.

$$CG(T) = CI + \sum_{j}\left[\sum_{t=1}^{T}\left(C_{a,t}(j) \times Rd_t\right) - VF_T(j)\right] \quad (1)$$

$$Rd = \frac{1}{(1 + RR/100)^t}\ [-] \quad (2)$$

$$RR = \frac{R - RI}{1 + (RI/100)}\ [\%] \quad (3)$$

$$VF_T(j) = VIC_j \times \left(1 + \frac{RX_j}{100}\right)^{(n_T(j) \times T_n(j))} \times \left[\frac{(n_T(j) + 1) \times T_n(j) - T}{T_n(j)}\right] \times Rd(T) \quad (4)$$

The Eq. (5) is the adapted version of the Eq. (1) to calculate the CG(T) in the EATEP. Where, CIG(T) is the Global Investment Cost, calculated with the Eq. (6); CRG(T) is the Global Running Cost, calculated with Eq. (7); CEG(T) is the Global Energy Cost, calculated with Eq. (8); and, CVG(T) is the Global Environmental Cost, calculated with the Eq. (9). As in the Eq. (1), in equations 5, 6, 7 and 8 the global economic flows are the sum of the current value of the annual economic flows updated to the initial year with the Rd. The equation of the CG(T) in the EATEP is presented in this format to indicate the global costs involved, its application in the evaluation of costs of EEP and EGP, and its adaptation to the calculation of income in the evaluation of EGP.

$$CG(T)_{(EEP,EGP)} = CIG(T)_{(EEP,EGP)} + CRG(T)_{(EEP,EGP)} + CEG(T)_{(EEP,EGP)} + CVG(T)_{(EEP,EGP)} \quad (5)$$

$$CIG(T)_{(EEP,EGP)} = \sum_{j} \left[\sum_{t=0}^{T} \left(CI_t(j)_{(EEP,EGP)} \times Rd_t(j) \right) - VF_T(j) \right] \quad (6)$$

$$CRG(T)_{(EEP,EGP)} = \sum_{j} \left[\sum_{t=1}^{T} CR_t(j)_{(EEP,EGP)} \times Rd_t(j) \right] \quad (7)$$

- Global Energy Cost, CEG(T), calculated with Eq. (8), is the cost of energy consumed, CECG(T), for each energy vector (*γ*). This equation contains the variable and fixed terms that are normally used to calculate the energy costs of consumers in liberalized markets. In addition, it contains variable additions, such as costs and rates that allow different energy cost structures to be configured. The variable term depends on the hourly amount of energy consumed and its price; and the fixed term equals the cost of access to the distribution network. In this way, the CECG(T) is calculated from the hourly Inputs of the energy consumed, EC, and its price, PEUC. In the evaluation of EEP the energy costs include as negative costs the income received by the energy exported to the network (CEPG). To calculate these costs, the same principle is followed of the variable and fixed terms of the energy consumed, but used here to evaluate the income received by the surplus energy exported. In this way the variable term depends on the exported energy, EP, and its PEUP price; the fixed term is included here with the Input CAEP. In both variable terms used in the calculation of the CEG(T) specific rates can be included, Tax (1) and Tax (4). Likewise, in the two fixed terms, AdCAEC and AdCAEP, additional costs may be included for the energy consumed and exported, with the intention of including, i.e. special tolls or the rental of measuring equipment. These fixed terms and their additional costs can be evaluated with independent rates, such as Tax (2) and Tax (5) for CAEC and CAEP respectively, and Tax (3) and Tax (6) for AdCAEC and AdCAEP respectively.

$$\begin{aligned} CEG(T)_{(EEP,EGP)} &= CECG(T)_{(EEP,EGP)} - CEPG(T)_{(EEP)} \\ &= \sum_{\gamma}\left[\sum_{t=1}^{T}\left(\left(\sum_{h=0}^{8760} EC_{h,t} \times PEUC_{h,t}\left(1+\frac{Tax_1}{100}\right)(\gamma)_{(EEP,EGP)}\right) + CAEC_t\left(1+\frac{Tax_2}{100}\right)(\gamma)_{(EEP,EGP)} \right.\right. \\ &\left.\left. + AdCAEC_t\left(1+\frac{Tax_3}{100}\right)(\gamma)_{(EEP,EGP)}\right) \times Rd_t(\gamma)\right] \\ &- \sum_{\gamma}\left[\sum_{t=1}^{T}\left(\left(\sum_{h=0}^{8760} EP_{h,t} \times PEUP_{h,t}\left(1+\frac{Tax_4}{100}\right)(\gamma)_{(EEP)}\right) + CAEP_t\left(1+\frac{Tax_5}{100}\right)(\gamma)_{(EEP)} \right.\right. \\ &\left.\left. + AdCAEP_t\left(1+\frac{Tax_6}{100}\right)(\gamma)_{(EEP)}\right) \times Rd_t(\gamma)\right] \end{aligned} \quad (8)$$

- Global Environmental Cost, CVG(T), calculated with Eq. (9). This cost is calculated from the energy exported by each energy vector (γ), its CO_2 emission factor, FCO2, and the price of emission rights per tonne of CO_2, PCO2. The current value is calculated using the RX of PCO2 in the discount rate.

$$\begin{aligned} CVG(T)_{(EEP,EGP)} &= \sum_{\gamma}\left[\sum_{t=1}^{T} CV_t(\gamma)_{(EEP,EGP)} \times Rd_t(CCO2)\right] \\ &= \sum_{\gamma}\left[\sum_{t=1}^{T}\left(\sum_{h=0}^{8760} EP_{h,t}(\gamma)_{(EEP,EGP)} \times FCO2_{h,t}(\gamma)_{(EEP,EGP)} \times PCO2_{h,t}(\gamma)_{(EEP,EGP)}\right) \times Rd_t(PC02)\right] \end{aligned} \quad (9)$$

Revenues Calculation

Executed with Eq. (10), this is the calculation procedure used to determine the economic flows of the sale of energy and CO_2 emission rights in the evaluation of EGP. Where, the Revenues in each hour of each year *t* (*IE_h,t*) of each energy vector (γ), are calculated from the amount of energy exported to the network and its price. *AdI* is a fixed value in this economic flow. Revenues from the sale of CO_2 emission rights, ICO2, are annual revenues whose current value is calculated using the RX of PCO2 on Rd.

$$IG(T)_{(\mathrm{EGP})} = \sum_{\gamma}\left[\sum_{t=1}^{T}\left(\sum_{h=0}^{8760} IE_{h,t}(\gamma)_{(\mathrm{EGP})}\right) \times Rd_t(\gamma) + ICO2(t)_{EGP} \times Rd_t(PCO2) + AdI(t)_{\gamma} \times Rd_t\big(AdI(t)_{\gamma}\big)\right] \quad (10)$$

In the EGP evaluation, the calculation of environmental costs and revenues from the sale of CO_2 emission rights depends on whether or not an established annual limit of emission rights assigned to the project is exceeded. If in any year *t* this limit is exceeded, environmental costs are recorded as the hypothetical purchase of the emission rights that cover this surplus. However, if this limit is not exceeded, the revenues from the sale of the emission rights not used are calculated.

2.3.3. Comparative Indicators

Benefits Indicators

Table 5 presents the equations used to calculate these indicators, which arise from transposing the interpretation of the calculation of benefits in EEP and EGP given in Table 1.

Output No. | Indicator | Acronym | [Unit]	EEP	EGP
6.1. Global Energy Benefit | BECG(EEP), BECP(EGP) | [Wh]	$= ECG_{P\_1}(T) - ECG_{P>1}(T)$	$= EPG_{P\_1}(T) - EPG_{P>1}(T)$
6.2. Global Environmental Benefit | BVG | [tCO_2]	$= VG_{P\_1}(T) - VG_{P>1}(T)$	$= VG_{P\_1}(T) - VG_{P>1}(T)$
6.3. Global Economic Benefit | BEG | [€]	$= CG_{P\_1}(T) - CG_{P>1}(T)$	$= ISCG_{P\_1}(T) - ISCG_{P>1}(T)$

Table 5. Equations for calculation of the Benefits Indicators. *p*: Package.

Comparative Ratios

These Indicators, presented in Table 6, serve to relate the Global Cost to the Benefits Indicators.

Output No. | Indicator | Acronym | [Unit]	Equation
7.1. Ratio of Global Cost by Global Energy Benefit | CGbyBENG* | [€/Wh]	$= CG(T)/BENG(T)$
7.2. Ratio of Global Cost by Global Environmental Benefit | CGbyBVG | [€/tCO_2]	$= CG(T)/BVG(T)$
7.3. Ratio of Global Economic Benefit by Global Cost | BEGbyCG | [%]	$= (BEG(T)/CG(T)) \times 100$
7.4. Ratio of Global Economic Benefit by Global Energy Benefit | BEGbyBENG* | [€/Wh]	$= (BEG(T)/BENG(T)) \times 100$
7.5. Ratio of Global Economic Benefit by Global Environmental Benefit | BEGbyBVG | [€/tCO_2]	$= (BGE(T)/BVG(T)) \times 100$

Table 6. Equations for calculation of the Comparative Ratios. (*) BENG: BECG in the equation of EEP and BEPG in the equation of EGP.

Financial Indicators

- Discounted Payback Period, DPP, calculated with Eq. (11), Output No. 8.1.: it is the number of years necessary to recover the initial investment, taking into account the value of money over time [25]. For this calculation, the current value of the Economic Benefit (BE) of each year is accumulated and compared with the initial investment cost. Adapted from [25].
- Return on investment, ROI, calculated with Eq. (12), Output No. 8.2.: is the number of times that the Global Investment Cost (CIG) is recovered with respect to the Global Economic Benefit (BEG). Adapted from [25].

$$\sum_{t=0}^{DPP} BE\ (t) = CII \tag{11}$$

$$ROI = \frac{BEG(T)}{CIG(T)} \tag{12}$$

Effect-Index

The Effect-Index is based on the Effect-Cost-Index proposed in [26]. It is the sum of the normalized values (from 0 to 1) of the economic, energy and environmental global indicators of the ratio of the Packages *p>1* to the Package 1, when Packages *p>1* get positive results in Benefits Indicators. The Effect-Index is called Effect-EEP-Index (EEPI) in the evaluation of EEP and Effect-EEP-Index (EGPI) in the EGP evaluation. To calculate them, Eq. (13) and Eq. (14), respectively, are used.

$$EEPI = \left(1 - \frac{CG_{P>1}(T)}{CG_{P\_1}(T)}\right)_{EEP} + \left(1 - \frac{ECG_{P>1}(T)}{ECG_{P\_1}(T)}\right)_{EEP} + \left(1 - \frac{VG_{P>1}(T)}{VG_{P\_1}(T)}\right)_{EEP} \tag{13}$$

$$EGPI = \left(1 - \frac{ISCG_{P>1}(T)}{ISCG_{P\_1}(T)}\right)_{EGP} + \left(1 - \frac{EPG_{P>1}(T)}{EPG_{P\_1}(T)}\right)_{EGP} + \left(1 - \frac{VG_{P>}(T)}{VG_{P\_1}(T)}\right)_{EGP} \tag{14}$$

Optimum Economic

This Comparative Indicator, based on the Cost-Optimal of the EPBD, serves to identify the Package that presents the optimum economic level among the Packages evaluated. In the evaluation of EEP this is called EEP-Optimal and serves to identify the Package with the lowest CG(T) that allows for the reduction of primary energy consumption. In the evaluation of EGP it is called EGP-Optimal and it serves to identify the Package with the highest ISC(T) that allows for the exportation of a greater amount of energy in terms of primary energy. Fig. 5 in graphs A, B and C presents the ideal results of these indicators. Graph A represents the EEP-Optimal in the configurations I and III; Graph B represents the EGP-Optimal in the II and IV configurations; and finally, Graph C represents the Optimum Economic in configuration V: the calculation of the EEP-Optimal and the EGP-Optimal in the evaluation of EEP-EGP scenario. Table 7 details these ideal results.

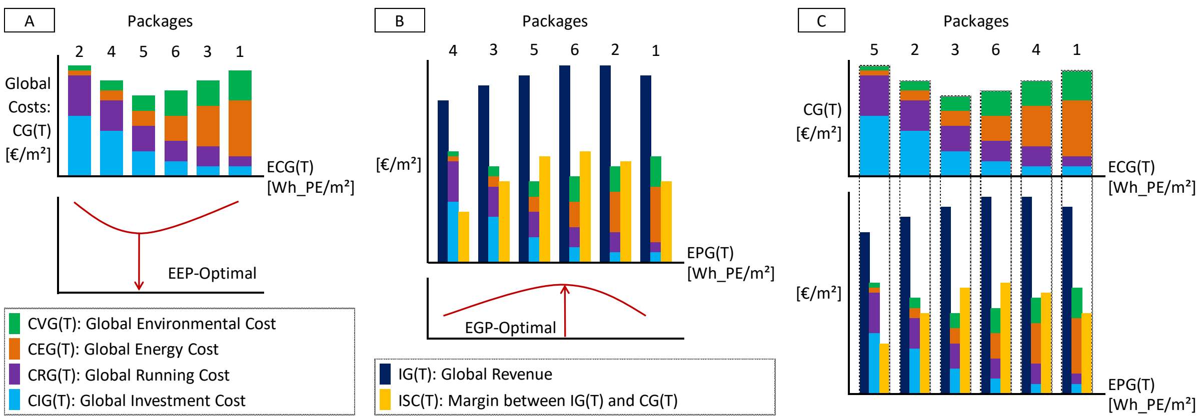

Fig. 5. Representation of the ideal graph of the Optimum Economic indicator: Graph A [17]. EEP-Optimal, configurations I and III. Graph B. EGP-Optimal, configurations II and IV. Graph C. EEP-Optimal with EGP-Optimal, configuration V.

Optimum Economic	Package closer to origin on the X axis	Optimal Package	Package 1 (Reference case)
EEP-Optimal (Fig. 5 - Graph A)	Package 2: Net-Zero Energy System. It presents the best result of energy consumption thanks to better EEMs and self-consumption technologies, which result in high CIG(T) and CRG(T).	Package 5: It has the lowest CG(T) and a minor energy consumption compared to the reference case.	It consumes more primary energy which leads to a high CEG(T) and CVG(T), and finally to a higher CG(T) regarding the other Packages. The CIG(T) and CRG(T) are low because it is a mature energy technology.
EGP-Optimal (Fig. 5 - Graph B)	Package 4: It exports the least amount of energy because it can be an energy generation technology with technical (intermittent, availability, etc.) or regulatory constraints, which prevents it from having higher IG(T). It also presents high costs which prevent it obtaining a higher ISC.	Package 6: It has the highest ISC(T) because its IG(T) are high and/or its CG(T) are relatively low.	It exports more energy than the other Packages but with high energy costs that prevent a higher ISC.
EGP-Optimal as a function of EEP-Optimal (Fig. 5 - Graph C)	In this EEP-EGP system, Package 3 demonstrates having the optimum result in the evaluation of the EEP, and the technologies necessary for the EGP to cover the external energy demand of the EEP.		

Table 7. Interpretation of ideal results of the Optimum Economic.

3. Validation of the EATEP

The validation of the EATEP with the evaluation of the two cases, is a bid to verify the whole spectrum of possibilities in its application. The simplest case uses its configuration in a broader evaluation, and the more complex case uses the configuration in its more limited evaluation. The first case has been named Validation Project No. 1 (VP1) and corresponds to the Evaluation Configuration I with seven Packages. The second case has been named Validation Project No. 2 (VP2) and corresponds to Evaluation Configuration V with a Package. Both validation projects reproduce works published in the reviewed literature, in order to verify that the results obtained with the EATEP are correct. Its reproduction also sought to validate the procedure for updating the economic values to the initial year with the use of evolution rates and inflation rates in the discount rate. Specifically, VP1 validated the updating procedure in the event that the rates of evolution of energy prices are equal to the inflation rate, and with VP2 in the case where these rates differ. The scope of the validation of the EATEP has been limited to the economic evaluation of the investment in the EEP and EGP energy systems. To represent the Inputs that could feed the EATEP-EEP and EATEP-EGP, Type 9 has been used to read the energy demand and available local resources from external files, and the Type Equa to perform the energy balance in EEP and EGP energy systems. Each of these validations is explained in detail below.

3.1. Description of the VP1

The VP1 validates the application of the EATEP, specifically the EATEP-EEP, in a project of nearly zero energy consumption in which several investment alternatives are studied. This is the case study of a single-family house in Oslo - Norway, published in [38], which, using standard EN 15459:2007 evaluates two renovation strategies aimed at obtaining a NZEB. The 262 m² house, uses electricity for heating and domestic hot water. The strategies evaluated are *Façade* and *Ambitious*. The first is an energy improvement of the facade and the second is an energy improvement in the whole house. Both strategies have heat recovery systems combined with two types of energy production systems.

3.1.1. Configuration of the Type EATEP-EEP

Table 8 presents the equivalence with the Packages evaluated in the EATEP-EEP, of the combination of EEMs and energy generation technologies used in the strategies Façade and Ambitious. Similarly, Table 9 presents the annual energy consumption data of these strategies and the reference case, together with the Packages of the EATEP-EEP in which they were entered as hourly data (dividing the annual data by 8760 hours). Table 10 presents the costs of the components. Where, Component 1 charges a subsidy of 20,400 EUR to the initial investment corresponding to the Ambitious strategy (Packages 2, 3 and 4). Finally, the VP1 has a T of 30 years, uses a RR calculated at 6.08%, a RX of electricity price of 5% and an electricity price of 0.125 EUR/kWh.

VP1	Characteristics	EATEP-EEP Package
Reference case (as built)	N/A	1

Ambitious Air to water heat pump	Extra EEMs (Floor heating - Hydronic) + Ventilation with heat recovery + Air to water heat pump	2
Ambitious Solar collector	Extra EEMs (Floor heating - Hydronic) + Ventilation with heat recovery + Flat plate solar collector	3
Ambitious Electric	Extra EEMs (Floor heating - Electric) + Ventilation with heat recovery	4
Façade + Air to water heat pump	EEMs (Floor heating - Hydronic) + Ventilation with heat recovery + Air to water heat pump	5
Façade + Solar collector	EEMs (Floor heating - Hydronic) + Ventilation with heat recovery + Flat plate solar collector	6
Façade + Electric	EEMs (Floor heating - Electric) + Ventilation with heat recovery	7

Table 8. Solutions evaluated in the VP1. Source: [38].

Heat production technologies of VP1 | Equivalent Package in the EATEP	Reference case		Façade		Ambitious	
	Renewable heat production [kWh]	Electricity for Heating [kWh]	Renewable heat production [kWh]	Electricity for Heating [kWh]	Renewable heat production [kWh]	Electricity for Heating [kWh]
Solar collector:	N/A	N/A	4700	12,300	4400	7100
Equivalent Package:			Package 6	Package 6	Package 3	Package 3
Air to water heat pump:	N/A	N/A	57,600	9400	5300	6200
Equivalent Package:			Package 5	Package 5	Package 2	Package 2
Electricity:	N/A	40,000	N/A	17,000	N/A	11,500
Equivalent Package:		Package 1		Package 7		Package 4

Table 9. Adaptation of the energy data of the VP1 to the Packages of the EATEP-EEP. Source: [38].

Component evaluated	Packages used in the EATEP-EEP					
	2	3	4	5	6	7
1: Basement walls (Tn = 60 Y)	15600	15600	15600	1600	1600	1600
Additional initial cost (Grant)	-20400	-20400	-20400	-	-	-
2: Wood frame walls (Tn = 60 Y)	14300	14300	1400	7100	7100	7100
3: Windows and doors (Tn = 30 Y)	9300	9300	9300	3400	3400	3400
4: Roof (Tn = 30 Years)	11900	11900	11900	-	-	-
5: Floor (Tn = 60 Years)	13900	13900	13900	-	-	-
6: Floor heating: Hydronic (Tn = 60 Y)	4100	4100	-	7100	7100	-
7: Floor heating: Electric (Tn = 60 Y)	-	-	3900	-	-	5800
8: Ventilation Heat Recovery (Tn = 15 Y)	9400	9400	9400	9400	9400	9400
Maintenance cost	188	188	188	188	188	188
9: Solar collector (Tn = 20 Y)	-	9900	-	-	9900	-
Additional initial cost (Grant)	-	-1250	-	-	-1250	-
Maintenance cost	-	198	-	-	198	-
10: Air to water heat pump (Tn = 15 Y)	11700	-	-	11700	-	-
Additional initial cost (Grant)	-1250	-	-	-1250	-	-
Maintenance cost	234	-	-	234	-	-

Table 10. Economic data (Cost [€]) of the VP1 entered in the Components of the EATEP-EEP. Tn: Lifespan. Y: Years. Source: [38].

3.1.2. Results of the VP1

The results of VP1 are presented in Table 11 and in Fig. 6, indicating only the indicators that are feasible to calculate with the data available in this project (so it is not possible to calculate the energy consumed in terms of primary energy and graph the EEP-Optimal). In the figure, Package 1, used as a reference case, only shows the energy costs. The results obtained, similar to those obtained in the replicated study, corroborate the operation of the EATEP-EEP: the best solution is the Façade heat pump, Package 5, where the initial investment is recovered in 12 years; the resulting global cost being 85,928 EUR and the Global Energy Cost 30,301 EUR. Fig. 6 also presents the result of the EEP-Effect-Index in each Package. Although Package 5 presents the best economic result, Package 4 is the one that presents the best result in this indicator (which omits the environmental results due to the lack of data on CO_2 emissions in the replicated study).

Indicator	Packages						
	1	2	3	4	5	6	7
2.1. ECG [kWh]	1200000	345000	345000	345000	510000	510000	510000
3. CG [€]	128501	100097	97061	95961	85928	89318	88148
3. CG [€/m²]	490	382	370	366	328	341	336
3.1. ICG [€]	0	72882	67577	55766	48330	43026	30284
3.1.1. IIC [€]	0	68550	66750	57900	39050	37250	27300
3.1.2.1. RMCG [€]	0	24758	19172	14654	19270	13684	9166
3.1.3. VF [€]	0	20426	18345	16788	9990	7908	6182
3.2. CRG [€]	0	7297	6675	3251	7297	6675	3251
3.2.1. CMG [€]	0	7297	6675	3251	7297	6675	3251
3.3. CEG [€]	128501	19918	22809	36944	30301	39617	54613
3.3.1. VCECG [€]	128501	19918	22809	36944	30198	39514	54613
3.3.2. FCECG [€]	0	0	0	0	103	103	0
3.5. CAA [€]	4283.38	3337	3235	3199	2864	2977	2938
6.1. BECG [kWh]	0	855000	855000	855000	690000	690000	690000
6.3. BEG [€]	0	28405	31440	32540	42573	39184	40353
7.1. CGbyBECG [€/kWh]	N/A	0.11707	0.11352	0.11223	0.1245	0.1294	0.1277
7.3. BEGbyCG [%]	N/A	28.38	32.39	33.91	49.54	43.87	45.78
7.4. BEGbyBECG [€/kWh]	N/A	0.03322	0.03677	0.03805	0.0617	0.0567	0.0584
8.1. DPP [Years]	N/A	23.1	22.5	20.6	12	12.7	10.7
8.2. ROI [Times]	N/A	0.39	0.47	0.58	0.88	0.91	1.33
8.1. DPP [Years]	N/A	23.1	22.5	20.6	12	12.7	10.7
9. EEPI [-]	N/A	0.93354	0.95716	0.96572	0.9063	0.8799	0.8890

Table 11. Results obtained with the EATEP in the VP1. Note: only the indicators that were possible to calculate with the original data of the VP1.

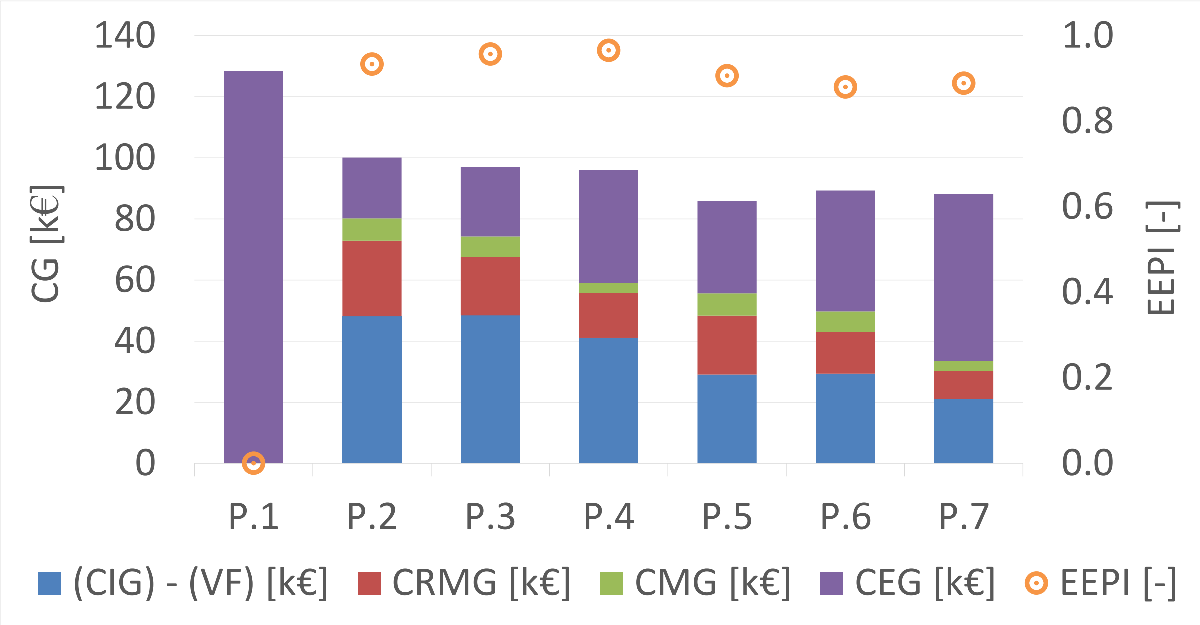

Fig. 6. Global Cost and Effect-EEP-Index of the VP1 obtained with the EATEP-EEP.

3.2. Description of the VP2

The VP2 validates the hypothetical case of a community of 1000 dwellings that invest in EEMs and cover their energy demand with electricity and Natural Gas (NG) from the network. The operation of the EATEP in the evaluation of an EEP-EG project has been corroborated, specifically:

1. Using the EATEP-EEP, investment in the EEMs of the community was economically evaluated. To this end, their homes were configured as two EEPs using the data in Example 1 of [16] (hereinafter referred to as Example 1): an EEP system with the accumulated data of 999 homes and another with the data of the remaining house. With the evaluation of this single house we have tried to replicate the calculation of the CG(T) presented in Example 1.
2. Using the EATEP-EGP, the investment in a system of renewable energy generation (photovoltaic) was evaluated economically, configured as an EGP system that covers a maximum of 30% of the demand for electricity in the community.

Fig. 7 presents the configuration of VP2 in TRNSYS. In this configuration four Types 9 were used to deliver the Inputs of the energy demand to two Types Equa that represent the energy balances of the EEP systems (EEP_1 and EEP_2); three other Types Equa were used to represent EGP power generation plants: EGP_1 represents the Photovoltaic Plant, EGP_2 represents an Electric Power Plant X and EGP_3 represents the NG supply plant. In this EEP-EGP project, losses in the transport and distribution of energy were omitted, only generation efficiencies were considered.

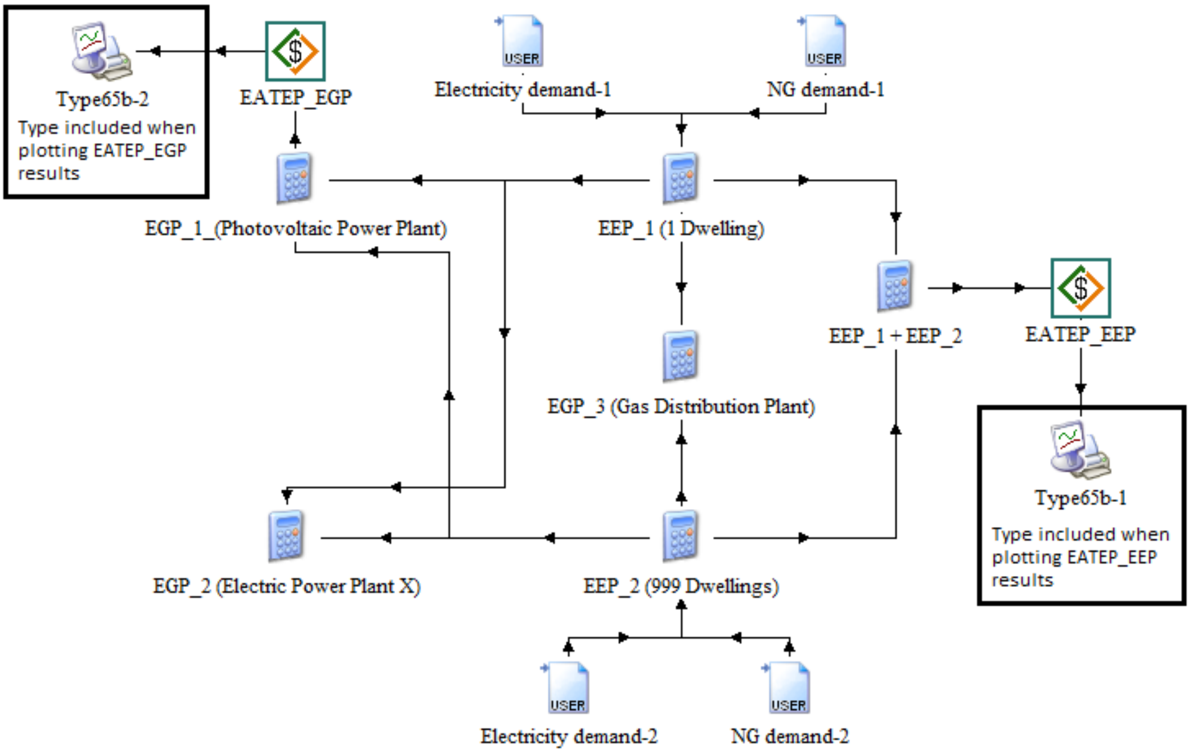

Fig. 7. Configuration of the VP2 and the Types EATEP-EEP and EATEP-EGP in TRNSYS 17. Note: The Types used were: 4 Types 9 to represent the electricity and NG demand; 5 Types Equa to represent the EEPs and EGPs.

3.2.1. Configuration of the Types EATEP-EEP and EATEP-EGP

Configuration of EATEP-EEP

The configuration of this Type was done by adapting the financial, cost and energy price data of Example 1 in the systems EEP_1 and EEP_2. This case evaluated the CG(T) of the construction of a 100 m^2 dwelling with natural gas and electricity systems. The investment in this project was evaluated over a period of 30 years, with an inflation rate of 2%, a market interest rate of 4.5% and 50 years of depreciation of the dwelling.

Table 12 presents the data related to the energy of Example 1 that were entered into the EATEP-EEP. The amounts of the energy are in annual values (12,233 kWh of NG and 680 kWh of electricity), but in the EATEP-EEP they are entered as hourly values (1.3965 kW of NG and 0.0776 kW of electricity). Energy prices and access costs are entered with VAT and additional taxes, and the annual cost of access to the electricity grid [€/year] is entered through the Input AdCAEC.

VP2: Example 1 of European Standard EN 15459:2007	
Item	Value
Natural Gas (NG)	
NG of heating system [kWh/Year]	9446
NG of Hot Water System (HWS) [kWh/Year]	2787
NG Price [€/kWh]	0.0275
RI of NG Price [%]	2
Annual cost of access to NG grid [€/Year]	103
RI of Annual cost of access to NG grid [%]	2
Electricity	
Electricity of ventilation system [kWh/Year]	680
Electricity price [$/kWh]	0.1023
RI of electricity price [%]	2
Annual cost of access to electric grid [€/Year]	57
RI of Annual cost of access to electric grid [%]	2

Table 12. Energy and economic data of Example 1, replicated in EEP_1 and EEP_2. Source: [16].

Table 13 presents the equivalence of the data related to the Components of Example 1, entered in the EATEP-EEP. The Replacement Costs of the evaluated measures were entered into six Components, with number 6 being used for the specific data of the dwelling and the Maintenance Costs.

VP2: Example 1 of European Standard EN 15459:2007 [16]	EEP_1 and EEP_2	
Item	Item	Value
Components with a 15 year lifespan:	Component 1:	
Heating. Generation: Combi boiler with flue 23 kW	Lifespan [Years]	15
	Cost [€]	1494
Components with a 20 year lifespan:	Component 2:	
{Heating. Emission: 8 steel radiators (including fixing and connection), thermostatic valve + Equilibrium valve + room thermostat} + {DHW. Emission: Mixing valve: 3. 42.68 Euro HT/unit. 2 in bathroom - 1 in kitchen} + {Ventilation. Generation Fan unit + gains}	Lifespan [Years]	20
	Cost [€]	4218
Components with a 25 year lifespan:	Component 3:	
{Building. Glazing and doors (External door, Service door (to garage. Shutters)} + {Heating system (Connection to Energy: Gas and Electricity)} + {Building. Ventilation. Emission (Air input, VMC in kitchen and bathroom) and Connection to electric board}	Lifespan [Years]	25
	Cost [€]	4072
Components with a 30 year lifespan:	Component 4:	
{Building. Glazing and doors. Insulating windows 4/12/4} + {Building. Cover Roof cover (wooden structure+terracosta cover)} + {Heating system. Distribution Steel pipe} + {Building. Domestic Hot Water. Distribution Copper Piping}	Lifespan [Years]	30
	Cost [€]	11440
Components with a 40 year lifespan:	Component 5:	
Building. Cover. Rockwool thickness: 200 mm [€]	Lifespan [Years]	40
	Cost [€]	1021
Components with a 50 year lifespan:	Component 6:	

{Building. Walls (Concrete Bricks, External cover, Insulation TH 38 8+1)} + {Building. Cover. Plaster coating} + {Building Floor (Floor structure concrete: thickness: 18 cm and Floor insulation)} [€]	Lifespan [Years]	50
	Cost [€]	15605
Maintenance costs per year [€]	Maintenance costs [€]	150

Table 13. Adaptation in the EATEP-EEP components of the VP2 data.

Configuration of the EATEP-EGP

The configuration of the EATEP-EGP consisted of adapting data from a Photovoltaic Power Plant in the EPG_1, together with the financial data used in the EATEP-EEP. An area of 200 m^2 was considered for this generation plant but the investment cost of the building was not considered. The EGP_1 was configured with a power of 24 kW to cover the 23.28 kW needed by the EEPs. To this end, photovoltaic modules with a yield of 18% and a useful life of 15 years were considered. The costs considered in the system were 4900 EUR/kW of initial investment and 0.224 EUR/kWh of operation, with annual evolution rates -2.4% and -2.6% respectively. This efficiency, these costs and their evolution rates correspond to data for the same period 2007-2008 of Example 1 and were taken from [38–40] (an equivalence of 0.7 EUR/USD [41] was used to convert the values of these references to euros).

3.2.2. Results of the VP2

Table 14 presents the comparison between the results of Example 1 and those obtained from the evaluation of EEP_1, EEP_2 with the EATEP-EEP, and in the evaluation of EGP_1 with the EATEP-EGP. Firstly, the results of the Rd are presented in the years in which the Components are replaced, followed by the results of the calculated indicators. The difference between the results of Example 1 and those obtained with the EATEP-EEP is due to the periodicity of the data entered: annual in the replicated case and per hour in the EATEP.

Indicator	Example 1 [16]	EATEP-EEP		EATEP-EGP
		EEP_1: 1 Dwelling	EEP_2: 999 Dwellings	EGP_1: PV power plant
1. Rd (*t* = 15) [-]	0.6954	0.6954	0.6954	0.6954
1. Rd (*t* = 20) [-]	0.6161	0.6161	0.6161	0.6161
1. Rd (*t* = 25) [-]	0.5459	0.5458	0.5458	0.5458
1. Rd (*t* = 30) [-]	0.4836	0.4836	0.4836	0.4836
2.1. GEC [MWh]	387.390	387.393	387006.086	33988.800
2.1. GEC_PE [MWh_PE]	N/A	0	0.00	33988.800
2.1. GEC_PE [MWh_PE/m²]	N/A	0	0.00	33.988
2.2. GEP [MWh]	N/A	0	0.00	6117.984
2.2. GEP_PE [MWh_PE]	N/A	0	0.00	33988.800
2.2. GEP_PE [MWh_PE/m²]	N/A	0	0.00	169.944

2.5. EBG [MWh]	387.390	387.393	387006.086	27870.816
2.5. EBG_PE [MWh_PE/m²]	N/A	0	0.00	135.955
3. CG [€]	53080	53056.54	53003483.46	910712.35
3. CG [€/m²]	531	530.57	530039.43	4553.56
3.1. GCI [€]	37974	37972.92	37934947.08	201850.59
3.1.1. IIC [€]	37850	37850	37812150.00	117600.00
3.1.2.1. CRMG [€]	12117	12115.99	12103874.01	84250.59
3.1.3. VF [€]	11993	11993.07	11981076.93	27442.16
3.2. GRC [€]	3160	3160.16	3156999.84	708861.76
3.2.1. CMG [€]	3160	3160.16	3156999.84	0.00
3.3. GEC [€]	11945	11923.46	11911536.54	0.00
3.3.1. VCECG [€]	8575	8552.62	8544067.38	0.00
3.3.2. FCECG [€]	3371	3370.84	3367469.16	0.00
3.5. CAA [€]	N/A	1768.55	1766781.45	30357.08
4.1. IEG [€]	N/A	0	0.00	439522.26
4.3. AdI [€]	N/A	0	0.00	1200861.77
4. IG [€]	N/A	0	0.00	1640384.03
4. IG [€/m²]	N/A	N/A	N/A	8201.92
5. ISC [€]	N/A	N/A	N/A	729671.68
5. ISC [€/m²]	N/A	N/A	N/A	3648.36

Table 14. Comparison of results of the VP2, in the Example 1 and EATEP. Note: only the indicators that were possible to calculate with the original data of the VP2.

4. Discussion

The operation of the EATEP has been validated with the VP1 and VP2. When evaluating a NZEB case in the VP1, the simplest configuration of the tool was validated in its broader scenario, when analysing several Packages. And, with the evaluation of the VP2, the application of the tool was validated in the evaluation of a system in which consumers and energy producers participate. The reproduction of these projects has specifically validated the procedure of updating the economic values to the initial year: with VP1 this procedure has been validated in the case in which the rates of evolution of energy prices are equal to the inflation rate, and with VP2 in the case where these rates differ from each other. The results highlight the versatility of the application of the EATEP in the analysis of the investments made in energy projects through the calculation of different indicators. As can be seen in Table 11, Package 7 presents the lowest value in the DPP indicator (expected period to recover the initial investment), 10.7 years, but the third lowest value in Global Cost, 88,148 EUR. The best solution in economic terms is the one presented by Package 5, which has the lowest value in Global Cost, 85,928 EUR, but a period of recovery of the initial investment greater than Package 7, 12 years. Similarly, Package 7 presents the penultimate lowest value in the Effect-EEP-Index. The highest value in this indicator, which adds the best economic,

economic-environmental results in relation to the reference case, is presented in Package 4. The difference in these results highlights the importance of calculating not only the investment required in energy projects, but also a greater variety of indicators with more specific objectives.

5. Conclusions

Clearly, the economic assessment of the technical and environmental performance of energy systems is indispensable in determining the viability of such investment. On the current world stage, analysing the transition to a low-carbon energy system with technical characteristics such as high energy efficiency and a significant presence of distributed generation, the technical-economic evaluation of the investments must take into account the expansion of NZEBs and the revenues perceived by the energy generation systems that supply the energy demand from the grid for these buildings. In this sense, the model presented in this paper and its use in TRNSYS with the creation of the EATEP-EEP and EATEP-EGP Types, permits the evaluation of the investment made by Consumers and Prosumers in NZEB and NPEB systems in its simplest configuration, as well as the investment made by Producers in power generation systems of any scale. And, in its most complex form, with these Types it is possible to evaluate systems that contemplate the interaction and exchange of energy and economic flows between Consumers, Producers and Prosumers, such as a community of nearly zero energy consumption. The EATEP has been validated by evaluating two cases that cover the different configurations which exist between these systems. This verifies its applicability and its versatility in the calculation of a wide variety of indicators. The two validated types are proposed here to include economic evaluation in the simulation of energy systems in TRNSYS, in parallel and in time steps, considering the following: the variation of energy flows as a function of economic factors, environmental costs, the costs of replacing the equipment and the evaluation of generation systems based on energy self-consumption systems in the investment scenario of a NZEC system.

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References

[1] Wang L, Gwilliam J, Jones P. Case study of zero energy house design in UK. Energy Build 2009;41:1215–22. doi:10.1016/j.enbuild.2009.07.001.

[2] Mateus T, Oliveira AC. Energy and economic analysis of an integrated solar absorption cooling and heating system in different building types and climates. Appl Energy 2009;86:949–57. doi:10.1016/j.apenergy.2008.09.005.

[3] Leckner M, Zmeureanu R. Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. Appl Energy 2011;88:232–41. doi:10.1016/j.apenergy.2010.07.031.

[4] Florides GA, Tassou SA, Kalogirou SA, Wrobel LC. Measures used to lower building energy consumption and their cost effectiveness. Appl Energy 2002;73:299–328. doi:10.1016/S0306-2619(02)00119-8.

[5] Romero Rodríguez L, Salmerón Lissén JM, Sánchez Ramos J, Rodríguez Jara EÁ, Álvarez Domínguez S. Analysis of the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/PV/micro-CHP systems. Appl Energy 2016;165:828–38. doi:10.1016/j.apenergy.2015.12.080.

[6] Kalogirou SA. Use a TRNSYS for modelling and simulation of a hybrid pv-thermal solar system for Cyprus. Renew Energy 2001;23:247–60. doi:10.1016/S0960-1481(00)00176-2.

[7] Mohan G, Kumar U, Pokhrel MK, Martin A. A novel solar thermal polygeneration system for sustainable production of cooling, clean water and domestic hot water in United Arab Emirates: Dynamic simulation and economic evaluation. Appl Energy 2016;167:173–88. doi:10.1016/j.apenergy.2015.10.116.

[8] Zhang L, Xu P, Mao J, Tang X, Li Z, Shi J. A low cost seasonal solar soil heat storage system for greenhouse heating: Design and pilot study. Appl Energy 2015;156:213–22. doi:10.1016/j.apenergy.2015.07.036.

[9] Kyriakarakos G, Dounis AI, Rozakis S, Arvanitis KG, Papadakis G. Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. Appl Energy 2011;88:4517–26. doi:10.1016/j.apenergy.2011.05.038.

[10] Allouche Y, Varga S, Bouden C, Oliveira AC. Dynamic simulation of an integrated solar-driven ejector based air conditioning system with PCM cold storage. Appl Energy 2017;190:600–11. doi:10.1016/j.apenergy.2017.01.001.

[11] Li Q, Zheng C, Shirazi A, Bany Mousa O, Moscia F, Scott JA, et al. Design and analysis of a medium-temperature, concentrated solar thermal collector for air-conditioning applications. Appl Energy 2017;190:1159–73. doi:10.1016/j.apenergy.2017.01.040.

[12] Alibabaei N, Fung AS, Raahemifar K, Moghimi A. Effects of intelligent strategy planning models on residential HVAC system energy demand and cost during the heating and cooling seasons. Appl Energy 2017;185:29–43. doi:10.1016/j.apenergy.2016.10.062.

[13] Tulus V, Boer D, Cabeza LF, Jiménez L, Guillén-Gosálbez G. Enhanced thermal energy supply via central solar heating plants with seasonal storage: A multi-objective optimization approach. Appl Energy 2016;181:549–61. doi:10.1016/j.apenergy.2016.08.037.

[14] Valdiserri P, Biserni C. Energy performance of an existing office building in the northern part of Italy: Retrofitting actions and economic assessment. Sustain Cities Soc 2016;27:65–72. doi:10.1016/j.scs.2016.07.009.

[15] Ackermann T, Andersson G, Söder L. Distributed generation: A definition. Electr Power Syst Res 2001;57:195–204. doi:10.1016/S0378-7796(01)00101-8.

[16] European Committee for Standardization. EN 15459:2007. Energy performance of buildings - Economic evaluation procedure for energy systems in buildings. n.d.

[17] European Union. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Off J Eur Union 2010:13–35. doi:10.3000/17252555.L_2010.153.eng.

[18] European Union. Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the

Council on the energy performance of buildings by establishing a comparative methodology framework for calculating. Off J Eur Union 2012:28. doi:10.3000/1977091X.C_2012.115.eng.

[19] European Union. Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology f 2012:1–28.

[20] Sesana MM, Salvalai G. Overview on life cycle methodologies and economic feasibility fornZEBs. Build Environ 2013;67:211–6. doi:10.1016/j.buildenv.2013.05.022.

[21] Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy Build 2013;56:189–203. doi:10.1016/j.enbuild.2012.08.023.

[22] GhaffarianHoseini A, Dahlan ND, Berardi U, GhaffarianHoseini A, Makaremi N, GhaffarianHoseini M. Sustainable energy performances of green buildings: A review of current theories, implementations and challenges. Renew Sustain Energy Rev 2013;25:1–17. doi:http://dx.doi.org/10.1016/j.rser.2013.01.010.

[23] Marique A-F, Reiter S. A simplified framework to assess the feasibility of zero-energy at the neighbourhood/community scale. Energy Build 2014;82:114–22. doi:10.1016/j.enbuild.2014.07.006.

[24] Kylili A, Fokaides P a. European smart cities: The role of zero energy buildings. Sustain Cities Soc 2015;15:86–95. doi:10.1016/j.scs.2014.12.003.

[25] Short W, Packey DJ. A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies 1995.

[26] Henning H, Wiemken E. Appropriate solutions using solar energy – basic com- parison of solar thermal and photovoltaic approaches n.d.;49:1–6.

[27] Connolly D, Lund H, Mathiesen B V, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. doi:10.1016/j.apenergy.2009.09.026.

[28] Collins S, Deane JP, Poncelet K, Panos E, Pietzcker RC, Delarue E, et al. Integrating short

term variations of the power system into integrated energy system models: A methodological review. Renew Sustain Energy Rev 2017;76:839–56. doi:10.1016/j.rser.2017.03.090.

[29] Manfren M, Caputo P, Costa G. Paradigm shift in urban energy systems through distributed generation: Methods and models. Appl Energy 2011;88:1032–48. doi:10.1016/j.apenergy.2010.10.018.

[30] Shrivastava RL, Kumar V, Untawale SP. Modeling and simulation of solar water heater: A TRNSYS perspective. Renew Sustain Energy Rev 2017;67:126–43. doi:10.1016/j.rser.2016.09.005.

[31] Ciulla G, Brano V Lo, Amico AD. Modelling relationship among energy demand , climate and office building features : A cluster analysis at European level. Appl Energy 2016;183:1021–34. doi:10.1016/j.apenergy.2016.09.046.

[32] S.A. Klein, Beckman WA, Mitchell JW, Duffie JA, Duffie NA, Freeman TL, et al. TRNSYS 17: A Transient System Simulation Program 2013;5:1–79.

[33] Massaguer E, Massaguer A, Montoro L, Gonzalez JR. Modeling analysis of longitudinal thermoelectric energy harvester in low temperature waste heat recovery applications. Appl Energy 2015;140:184–95. doi:10.1016/j.apenergy.2014.12.005.

[34] Rysanek AM, Choudhary R. Optimum building energy retrofits under technical and economic uncertainty. Energy Build 2013;57:324–37. doi:10.1016/j.enbuild.2012.10.027.

[35] Klein SA, Beckman WA, Mitchell JW, Duffie JA, Duffie NA, Freeman TL, et al. TRNSYS 17 a TRaNsient SYstem Simulation program, Volume 3, Standard Component Librar y Overview 2011;3:60.

[36] Thermal Energy System Specialists (TESS). TESS Component Libraries - General Descriptions. Madison, WI: 2014.

[37] Siano P. Demand response and smart grids—A survey. Renew Sustain Energy Rev 2014;30:461–78. doi:http://dx.doi.org/10.1016/j.rser.2013.10.022.

[38] Risholt B, Time B, Hestnes AG. Sustainability assessment of nearly zero energy renovation of dwellings based on energy, economy and home quality indicators. Energy

Build 2013;60:217–24. doi:http://dx.doi.org/10.1016/j.enbuild.2012.12.017.

[39] Battaglia C, Cuevas A, De Wolf S. High-efficiency crystalline silicon solar cells: status and perspectives. Energy Environ Sci 2016;9:1552–76. doi:10.1039/C5EE03380B.

[40] Energy S. Photovoltaics report. Freiburg: 2016. doi:26.05.2014.

[41] International Energy Agency. World Energy Outlook 2008. vol. 23. 2008th ed. Paris: OECD/IEA; 2008. doi:10.1049/ep.1977.0180.