Geo-SIV: a new free tool MATLAB-based for the preliminary technical, economic and environmental evaluation of small to medium shallow geothermal energy projects in Catalonia based on GIS datasets

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ABSTRACT

This work describes the main features of Geo-SIV, a new free-access calculation tool for preliminary assessment of small-to-medium shallow geothermal energy (SGE) projects in the territory of Catalonia. This tool has been conceived to stimulate awareness among the Catalan population about SGE and to boost its associated growing market. Geo-SIV is presented as a stand-alone application (or *app*). It has been coded in MATLAB ® and compiled for WINDOWS ®. The source code is published in the GitHub repository of the ICGC: https://github.com/OpenICGC/Geo-SIV. The *app* is divided into two main modules: The sizing and simulation (S&S) module, and the economic and environmental (E&E) module.

The S&S module allows the sizing of a borehole heat exchanger (BHE) field coupled to a ground-source heat pump (GSHP), given a specific location, a thermal demand pattern and a GSHP with specific nominal capacity and performance.

In the E&E module the user can create different comparative scenarios between the simulated GSHP system and an alternative solution, either considering a new building or the substitution of an existing installation. For the alternative solution, the user is requested to combine one or multiple renewable and/or non-renewable technologies for heating, cooling and domestic hot water (DHW) production. The comparative scenario also comprises external funding like subsidies or loans. Moreover, Geo-SIV includes a novel feature that allows to define climatization installations as hybridised with solar photovoltaic (PV) energy.

1 INTRODUCTION

1.1 Local context motivation

According to the database of shallow geothermal energy (SGE) installations in Catalonia, there is a still incipient deployment of this renewable technology throughout the territory, accounted for in 42 MWt of thermal power (installed, under construction or projected) (ICGC, 2021). However, in the last two years a remarkable growth rate has been experienced, close to 20%/year, where more than 80 % of the installations are based on closed-loop vertical borehole heat exchangers (BHEs).

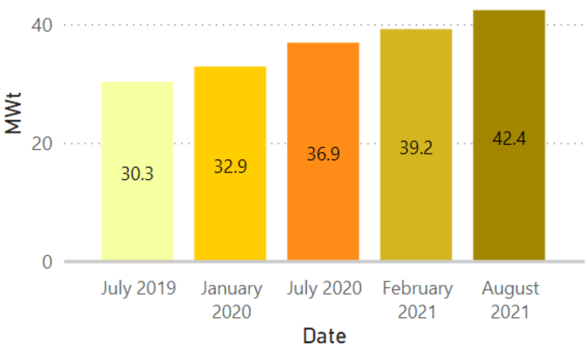

Figure 1: Evolution of the heat power inventoried in the Database of shallow geothermal installations of Catalonia (source: BdIGSCat, ICGC).

Nomenclature

COP	Coefficient of performance [-]
EER	Energy Efficiency ratio [-]
SPF	Seasonal Performance Factor [-]
T	Temperature [ºC]
F	Load Factor [-]
r	Effective thermal resistance [mK/W]
q	Power or "Thermal load" [W]
E	Energy or "Demand" [Wh]
c_0	Zero-order linear coefficient [-]
c_1	First-order linear coefficient [W/K]
h	Yearly occurrence of T_{ext} [hours]
L	Total length of the BHE field [m]
OPEX	Operational expenditure [€]
CAPEX	Capital expenditure [€]
EXP	Expenditure [€]
CF	Cash Flow [€]

Subscripts or Superscripts

ext	Exterior (refers to dry-bulb temperature)
h	Heating (heat pump operating mode)
c	Cooling (heat pump operating mode)
DHW	Domestic Hot Water (heat pump operating mode)
d	Design
b	Balance
p	Probe
g	Ground
ewt	Entering water temperature
min	Minimum average (between in and out) value
max	Maximum average (between in and out) value
m	Monthly
i	Refers to the operating mode, "*h*" or "*c*"
k	Refers to the type of thermal load
geo	Refers to the SGE installation
alt	Refers to the compared alternative installation
t	Refers to a year within the lifespan of the project
j	Refers to the number of a bin temperature where $T_j - 1℃ \leq T_{ext} < T_j + 1℃$

SGE deployment is still low if compared to other renewable technologies in Catalonia, but it is clearly gaining momentum. The fact is that the heat pump market in Spain is huge, mostly due to air-to-air systems (air-conditioning units). However, the installation of air-to-water heat pump has experienced a considerable growth in the previous decade, from 3259 units sold in 2010, to 32561 units in 2018. As a comparison, 87104 air-to-air units were sold in 2018. In contrast, less than 300 ground source heat pump (GSHP) units were sold in the same year (Witkowska A. et al. 2021). Apparently, so far Spain has demonstrated little interest for GSHPs, which applies also in the Catalonia. There are many reasons for this huge gap between air-to-water and GSHPs, like the specific clime characteristics, the predominant building architecture or even the national regulatory frame concerning borehole drilling. However, after all there is still a cultural barrier that needs to be overcome. The Catalan business ecosystem possesses a strong background in the exploitation of the SGE resource and its associated technologies, backed by over 20 years of experience. Now, the moment has come to promote a steady growth of SGE installations in the forthcoming years. Hence Geo-SIV has been conceived to generate a more realistic perception of SGE and its benefits among the Catalan population.

1.2 Geo-SIV among the existing alternatives.

Most of the professionals in the SGE market are aware of software tools that allow designers to size SGE installations in a comprehensive manner, including also the economic and environmental perspective. Ground Loop Design (Thermal Dynamics, 2016), Earth Energy Designer (Blocon, 2021) and GLHEPro (OSU, 2007) are good examples of commercial products targeting an audience with a high degree of knowledge about SGE.

On the side of free tools, there are also interesting examples. The G.POT method developed by the *Politecnico di Torino* (Casasso A. and Sethi R., 2016) is a simple methodology that permits a quantitative evaluation of the shallow geothermal potential depending on the location for a given borehole length. This tool is very useful to generate contrast maps to compare how much heat can be exchanged with the ground (yearly heating or cooling demand) throughout a certain territory (Arnó G. et al., 2019).

Created under the framework of the Cheap-GSHP project (Call H2020-LCE-2014-2), a decision support system (DSS) was built and released in the form of a web application. It allows a fast sizing of a BHE field and its associated GSHP (De Carli M. et al., 2019). Although the idea is ambitious, the territorial scope is probably too large (European scale) to guarantee accurate results, especially when it comes to geological data. Moreover, the level of interaction with the user is restricted to a very limited set of parameters.

Ges-CAL is also a free application coded in Phyton and created by the Universidad de Salamanca (Sáez-Blázquez C. et al., 2020). It shows the most similar approach to Geo-SIV, since it allows the sizing and economic analysis of SGE installations at a local level (Ávila province, Spain). It differs mainly on the accessibility of the general public to the tool, the design of the graphical user interface (GUI) and the possibility to hybridise the SGE installation with solar photovoltaic (PV) energy, which is one of the most appealing and novel features of Geo-SIV.

Geo-SIV *app* is aimed at a wide range of users and stakeholders, from people with a basic SGE background, to engineers, architects or geo-technicians, among others. Its main purpose is to increase awareness about SGE and GSHPs as a renewable resource and a highly efficient technology, respectively. Although Geo-SIV allows to perform quantitative analyses of real scenarios, it is overall an educational tool.

2 WHAT IS IT WHAT CAN IT DO

2.1 What is Geo-SIV?

Geo-SIV is presented as a stand-alone application created by MATLAB app designer ® (version R2020a) from Mathworks Inc., and compiled for WINDOWS® environment. It has been developed by the Geological Resources Department from the Institut Cartogràfic i Geològic de Catalunya (García-Céspedes J. et al., 2022), in collaboration with the TIC, Industrial and Mining Engineering Department from the Universitat Politècnica de Catalunya (UPC).

Figure 2: Geo-SIV loads geological data according to the location specified by the user automatically, prior to the size, simulation and economical and environmental analysis of the SGE installation.

2.2 What can Geo-SIV do?

The *app* loads automatically climate data and thermal properties of the ground from GIS raster layers containing estimated basic parameters. The user can choose between two territorial scopes. The one selected by default covers the entire territory of Catalonia. Alternatively, the user is able to opt for the specific urban and peri-urban area of Girona, so an even more accurate geological information is provided thanks to the experimental work carried out in the frame of the GeoERA MUSE project (Cypaite V. et al., 2021).

Geo-SIV is conceived and designed to:

- Estimate the thermal load and the demand of different types of building considering simplified geometries and different distribution systems, in case these values are unknown.
- Size a specific SGE installation based on closed-loop vertical BHEs. The *app* only permits the sizing of installations limited to 70 kW, since this is the threshold beyond which a more detailed study would be required, in compliance with the Spanish standard UNE-100715 (AENOR,2014). Despite the *app* is valid only for locations within the limits of Catalan territory, the methodology can be extended to any other region if ground and climate data are available.
- Assess the monthly and yearly performance of the resulting SGE installation considering the selected location.
- Perform an economical and environmental analysis through the comparison of the upfront costs (or $CAPEX$), cash-flow (CF) time-evolution and CO_2-equivalent emissions of the SGE installation and analogous alternatives based on biomass, common fossil fuels or aerothermal systems.
- Consider scenarios where any of the thermal installations under comparison can be hybridised with solar PV panels and batteries.
- Generate a final report with all the input data and the obtained results.

3 METHODOLOGY

3.1 Models behind Geo-SIV

Geo-SIV adapts the modified bin method presented in ASHRAE (1985) for the estimation of the thermal load and demand of generic buildings. In this method, it is assumed a linear dependency (see figure 3) between the dry bulb ambient temperature and 6 different components of the thermal load (heating and cooling), namely:

- Transmission losses/gains
- Solar gains
- Internal latent heat losses/gains
- Internal sensible heat losses/gains
- Fresh air latent heat losses/gains.
- Fresh air sensible heat losses/gains.

Each k term of the thermal load is represented by a linear equation:

$$q_k^i(T_j) = c_{0,k}^i + c_{1,k}^i T_j \qquad (Eq.\ 1)$$

And the total thermal load is the summatory:

$$q^i(T_j) = \sum_{k=1}^{6} q_k^i(T_j) \qquad (Eq. 2)$$

The demand is the product of the thermal load times the occurrence (number of hours):

$$E_j^i = q^i(T_j)h(T_j) \qquad (Eq. 3)$$

Note that the modified bin-method only applies to heating and cooling demands, but not to domestic hot water (DHW), since there is no sense in considering a linear dependence between DHW demand and T_{ext}.

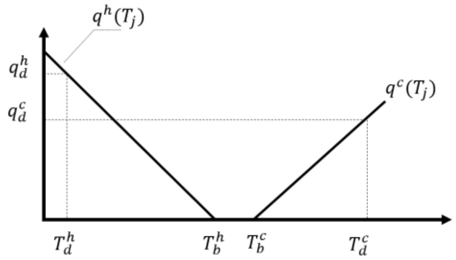

Figure 3: Generic plot of the linear dependence between the thermal load and the ambient dry-bulb temperature.

Nevertheless, Geo-SIV estimates the monthly and yearly DHW demand based on the specified occupancy of the building and the tap water temperature along the year. The expression for the entire monthly demand is considered as:

$$E_m = \sum_{T_j<T_b^h} q^h(T_j)h_m(T_j) - \sum_{T_j>T_b^c} q^c(T_j)h_m(T_j) + E_m^{DHW} \qquad (Eq. 4)$$

The sizing of the BHE field is based on the Kelvin's line-source theory adopted by the IGSHPA (Claesson J. and Eskilson P., 1988), and is adapted to account also for the DHW load and demand:

$$L_h = q_{h,DHW}^d \left[\frac{\left(\frac{COP-1}{COP}\right)\left(r_p + r_s(F_h + F_{DHW})\right)}{T_g^{min} - T_{ewt}^{min}} \right] \qquad (Eq. 5)$$

$$L_c = q_c^d \left[\frac{\left(\frac{EER+1}{EER}\right)\left(r_p + r_s F_c\right)}{T_{ewt}^{max} - T_g^{max}} \right] \qquad (Eq. 6)$$

Where $q_{h,DHW}^d$ is the maximum value of heating thermal load between q_h^d and q_{DHW}^d . This is especially relevant in buildings with a high DHW demand like sport centres.

The final length of the BHE field is automatically chosen by Geo-SIV as the longest between heating/DHW and cooling modes, since the design criteria is that the resulting SGE installation must meet the entire demand of the building.

In case that the SGE installation show a remarkable yearly imbalance between injected and extracted heat from the ground, the user can optionally take into consideration possible deviations of the undisturbed ground temperature T_g^0 along the years. This correction has been implemented by means of a simplistic model built out of Fourier's heat conduction law. The resulting temperature variation ΔT_g^0 must be understood as an upper limit, since no heat abstraction effects are considered in the model.

Concerning hybridization with solar PV energy, the Geo-SIV team has developed its own methodology. Basically, attending to the value of T_{ext}, production of thermal energy by the thermal installation and electricity from solar panels are compared for each hour of the year. This way, it is possible to determine how much self-produced power is consumed instantly by the thermal installation, which portion is injected to the electric grid and which one is stored (if there are batteries). The algorithm to calculate this assumes the following priority sequence, applied hour after hour for a whole year:

1. Self-produced power must be consumed instantly, when possible, by the thermal installation.
2. If there is not enough self-produced power to meet the demand (under heating or cooling mode), power from batteries must be used.
3. If self-produced power exceeds the demand, the excess electricity should be used first to produce DHW, and second, to charge the batteries. Finally, if no more DHW can be produced or the batteries are full (or there are no batteries), then the excess power must be injected to the grid. A feed-in-tariff scheme is considered for the economic compensation of injected power to the grid, according to the current Spanish regulatory frame (MITECO, 2019)

Additionally, Geo-SIV will never consider the use of electricity stored in batteries to produce DHW.

3.2 Data that feed the models

The climatic data that feeds the models are obtained from the Spanish Ministry of Transport, Mobility and Urban Agenda (MITMA) through the national Technical Building Code (CTE) (MITMA, 2019). From these sets, Geo-SIV uses hourly-resolved values of:

- Mean dry bulb temperature (ºC)
- Relative humidity (%)
- Direct and Diffuse Horizontal irradiation (W/m^2)
- Sun azimuth and zenith position (º)

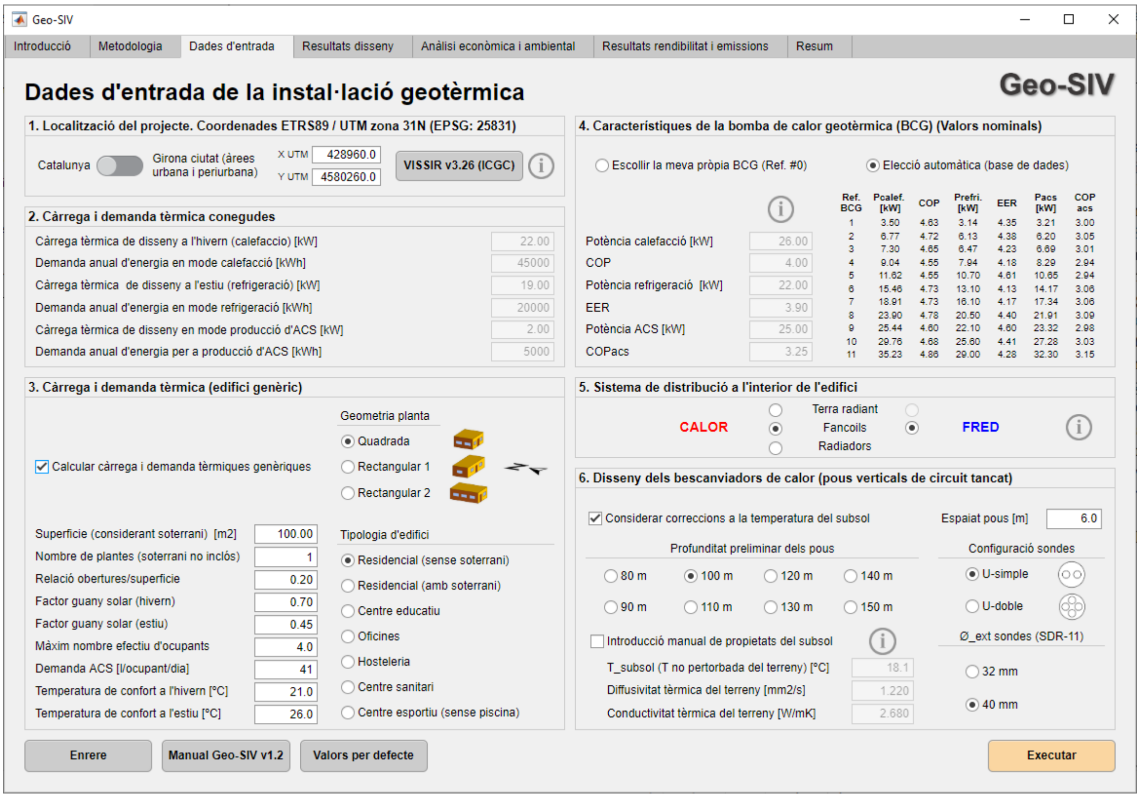

Figure 4: Screenshot of the GUI showing the tab for input data for the size and simulation of the SGE installation.

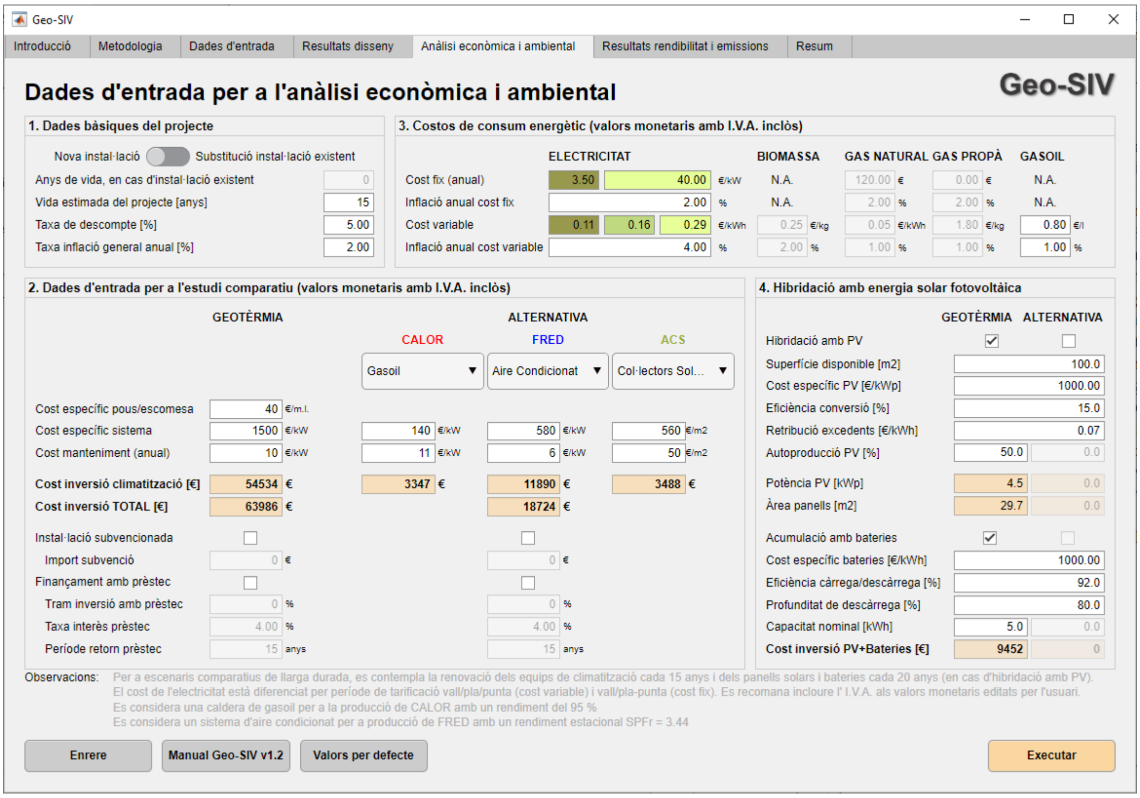

Figure 5: Screenshot of the GUI showing the tab for input data concerning the economic and environmental analysis. This tab activates only after a SGE installation has been performed.

Moreover, Geo-SIV includes the values for the winter and summer design dry bulb temperatures (T_d^h and T_d^c, respectively), and humidity, as well as the recommended values for the thermal transmittance [W/m^{2}K] of building parts (windows, walls, ceilings, etc.), also from the CTE.

Concerning geological data, Geo-SIV incorporates different GIS raster layers generated by the ICGC:

- Interpolated values of average ground thermal conductivity (grid resolution of 270m for Catalonia and 10 m for Girona area).
- Interpolated values of average ground thermal diffusivity (grid resolution of 180m for Catalonia and 10 m for Girona area).
- Interpolated values of estimated ground temperature at depths of 50, 100 and 150 m. (grid resolution of 90 m for Catalonia and 10 m for Girona area).

The values used under the territorial scope of Girona are the result of integrated 3D models and recent (2018-2019) thermal response test (TRT) assays along with data gathered by a network of monitored boreholes set up by the ICGC (Cypaite V. et al., 2021).

Finally, Geo-SIV incorporates a set of assumed values from which the most relevant are listed below:

- Geometric characteristics of the generic buildings (height of the walls, number of doors etc.).
- Specific fresh-air renovation rate.
- Specific gains due to appliances, illumination or occupants.
- Nominal performance data of the internal GSHPs incorporated by the app, as well as those of the aerothermal heat pumps which are used in the economic analysis and the rest of thermal technologies.
- Conversion factors for the different energy sources (kWh/l_{petrol}, kWh/$kg_{biomass}$, etc.)
- Basic characteristics of solar PV installations (inclination of panels, minimum space between panels, etc.)

The app employs 125 different parameters for its calculations. From this set, the user can edit manually up to 86 (~70%). However, default values are provided in most of the cases. Most of the parameters requested by Geo-SIV concerns the economic and environmental analysis. Here the user will be able to select between two scenarios: a new building, or an existing installation that is replaced by SGE. The lifespan of the project is set as 15 years by default, although it can be increased up to 50. In any case, replacement of the main equipment (boilers, heat pumps) is assumed to be requested every 15 years. PV solar installations are considered to last for 20 years (panels and even batteries), and the BHE field is assumed to last for at least 50 years.

4 DISPLAY OF RESULTS

The calculations performed by Geo-SIV can be divided into two modules, the sizing and simulation module (S&S), and the economic and environmental (E&E) analysis module.

4.1 The S&S module.

The main results of the S&S module are divided into 4 blocks:

- **BHE field**. On the one hand, the number of BHE and mean length are shown along with the estimated surface area needed to construct it, assuming a square grid. On the other hand, it is shown the yearly heat balance of the ground and the estimated value of ΔT_g^0 and the corresponding period.
- **GSHP**. Here Geo-SIV shows the nominal values of the GSHP considered in the SGE installation.
- **Fluid thermal conditions**. The maximum and minimum values of the brine (or pure water) temperature at the BHE field, T_{ewt}^{max} and T_{ewt}^{min}, are calculated by imposing the gap between T_g^0 and T_{ewt}^{max} and T_{ewt}^{min}. This actually contributes to the iterative process leading to the final length of the BHE field:

$$T_{ewt}^{min} = \frac{\left(T_g^0 - 7℃\right) + \left(T_g^0 - 10℃\right)}{2} \qquad (Eq.7)$$

$$T_{ewt}^{max} = \frac{\left(T_g^0 + 10℃\right) + \left(T_g^0 + 15℃\right)}{2} \qquad (Eq.8)$$

  This criterion is purely empirical, although the purpose is clear: a trade-off must be achieved for the temperature jump between the ground and the GSHP (see Eq.5 and 6: The largest the the better to maximise heat exchange with the ground and minimise BHE length, and the shortest the better to improve GSHP operation efficiency).
- **SGE installation performance**. The user can get an idea of what would be the total production of thermal energy and the power consumption to achieve it. Additionally, the seasonal performance factor (SPF) is estimated for each mode of operation. These values are taken as the starting point for the economic and environmental analysis.

Finally, two pairs of plots are presented below the results. The left plot can shift from displaying $q^i(T_j)$ to $E^i(T_j)$. The right plot displays E_m^i, shifting from thermal energy production to power consumption. Actually, the user will be able to distinguish between three types of power consumption each month, since the current Spanish regulation obliges to establish separate tariffs depending on the hour of the day (“peak”, “standard” and “off-peak” time bands) (see figure 6).

Figure 6: Screenshot of the GUI showing the tab for the display of the results concerning the size and simulation of the SGE installation.

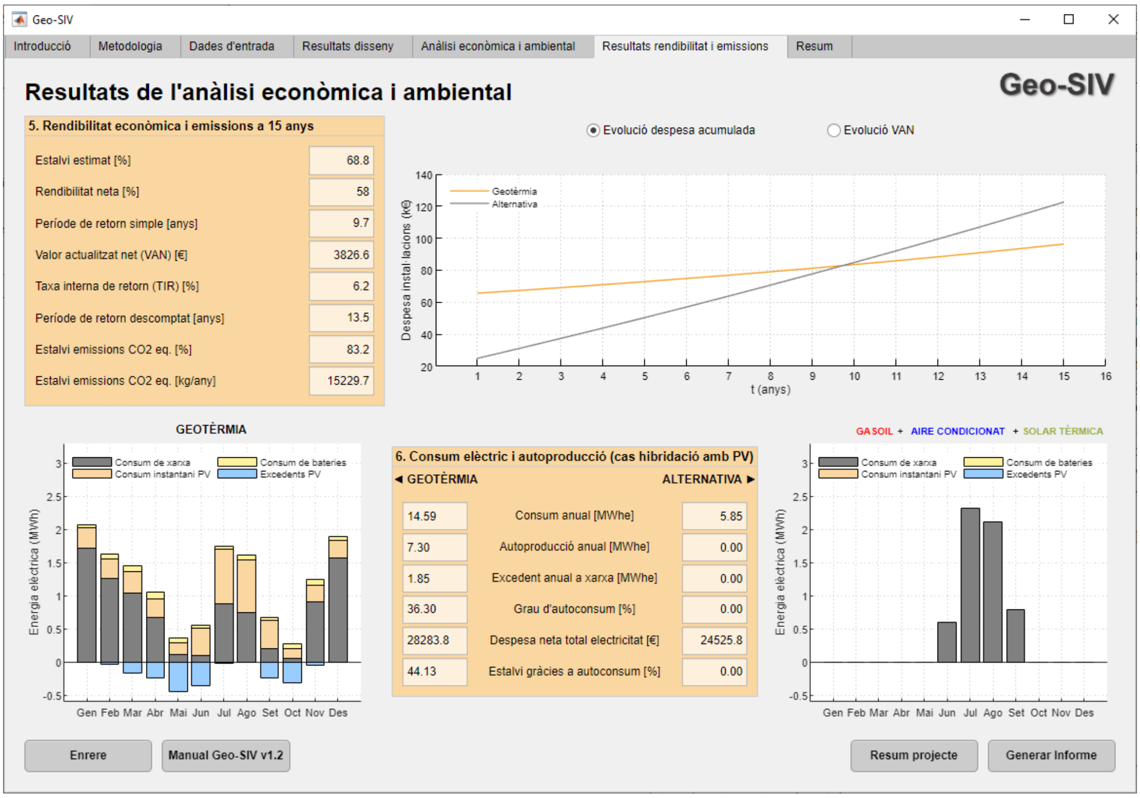

Figure 7: Screenshot of the GUI showing the tab for the display of the results concerning economic and environmental analysis of the SGE installation as compared with an alternative one.

4.2 Results of the E&E module

The main results of the E&E module are based on the time-evolution of the CF compared to an initial investment. In this case, the initial investment is the surplus $CAPEX$ of SGE installations with respect to an alternative installation.

Regarding the CF, it originates from the yearly savings hypothetically a SGE installation would cause thanks to its unsurpassed lower $OPEX$. Analogously, the environmental analysis is based on the savings in CO_2-equivalent emissions caused by the superior efficiency of SGE installations. The result of the analysis is shown mainly as a set of economic and environmental indicators, namely:

- **Estimated savings [%]**. They are the relative savings in the operation costs:

$$100 \cdot \frac{OPEX_{alt} - OPEX_{geo}}{OPEX_{alt}} \qquad (Eq. 9)$$

- **Net profitability [%]**. Here it is defined as the ratio between cumulative expenditure difference and CAPEX difference:

$$100 \cdot \frac{EXP_{alt}^{total} - EXP_{geo}^{total}}{CAPEX_{geo} - CAPEX_{alt}} \qquad (Eq. 10)$$

- **Payback time [years]**. It is the period of time needed for the cumulative EXP_{alt} to surpass the value of cumulative EXP_{geo}.
- **Net Present Value (NPV) [€]**. It is interpreted as the extra benefit of the project under study when compared with an alternative low risk project defined by a discount rate dr:

$$NPV = CAPEX_{geo} - CAPEX_{alt} + \sum_{t=1}^{t=n} \frac{CF|_t}{(1+dr)^t} \qquad (Eq. 11)$$

- **Discounted payback time [years]**. It is the period of time needed for the cumulative NPV to achieve a positive value. This will be always higher than the payback time, and it is usually considered as a more restrictive indicator of the project profitability.
- **Internal return rate (IRR) [%]**. It is the value of dr that would make NPV go to zero. Whenever IRR>dr, the project is considered as attractive.
- **CO_2-equivalent emissions savings**. It is provided as a relative value [%] and a yearly absolute value [kg_{CO2eq}/year]

Apart from the main economic and environmental indicators, Geo-SIV presents the compared power consumption for both the SGE and the alternative installation. This part is relevant mostly when any installation is hybridised with PV solar energy. In the plots it is possible to distinguish between the instantly-consumed self-produced power (orange), the power consumed from batteries (yellow), the power consumed from the grid (grey) and the excess power injected to the grid (blue). Additional numerical indicators are shown in parallel (see figure 7).

A final tab is presented by the user graphical interface with a summary of the analysed project, showing the most important input data and results. This way, the user gets a "big picture" of the project. Besides, it is possible to generate comprehensive reports in .txt format, either at the S&S results tab or the E&E results tab (figures 6 and 7, respectively). In the first case the report only accounts for the S&S results. In the latter case, the report includes all the results.

5 SUMMARY AND CONCLUSIONS

A new, user-friendly, free and educative tool has been presented. Geo-SIV is open to a wide range of potential users, who will be able to estimate the size and performance of small-to-medium size SGE installations based on closed-loop vertical BHEs, as well as to analyse its economic profitability (at least in a preliminary manner). The GUI presents a moderate number of freedom degrees to help the user to learn about the relevance of key aspects of SGE. The influence of the climate, the ground properties, the type of building or the distribution system in the performance of a SGE installation can be easily explored. Although the results from Geo-SIV runs cannot be considered binding enough when it comes to project drafting, they surely will contribute to decision-making. The main purposes behind Geo-SIV are closely linked to the specific context of Catalonia. Because of its particular characteristics, the SGE resource shows a great potential that has not been truly tapped yet in Catalonia. Higher awareness among the population and public bodies is expected thanks to initiatives like this. Within the business ecosystem, Geo-SIV must be understood as a bridge between potential customers, installers, architects, engineers and geo-technicians.

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