Suitability of Test Reference Year for performance assessment of buildings with PV-battery system

Citation for published version (APA):

Document license:
Unspecified

Document status and date:
Accepted/In press: 01/01/2023

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Suitability of Test Reference Year for performance assessment of buildings with PV-battery system

Riccardo Gazzin¹, Zahra Mohammadi², Roel Loonen³, Giovanni Pernigotto¹, Andrea Gasparella¹, Jan Hensen²

¹Faculty of Engineering, Free University of Bozen-Bolzano, Bolzano, Italy
²Department of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands

Abstract
This study investigated the representativeness of Test Reference Year (TRY) for the estimation of the performance of a system with photovoltaic (PV) modules and a battery energy storage system (BESS) in a high performance building. According to the technical standard EN ISO 15927-4:2005, the TRY is an artificial year made of 12 actual months selected according to the Finkelstein-Schafer statistics. Even if it commonly used as boundary condition in building performance simulation, the procedure adopted for its definition does not explicitly consider the representativeness of short-term dynamics, such as daily and hourly sequential patterns of weather variables. This can introduce limitations to assess specific systems in modern buildings, such as PV and BESS, since hourly and daily sequences can affect charge and discharge cycles of the battery.

In order to study this problem, a three-floor semi-detached terraced house equipped with a PV-BESS was used as case study, considering both multi-year and TRY weather data for three locations, i.e., De Bilt in the Netherlands, Trento and Padova in Italy. After comparing monthly heating degree-days and solar irradiance values of multi-year and TRY weather files, their impact on the simulated performance of the PV-BESS was examined at both monthly and annual scale. Results show that, in the studied locations, TRY weather files proved to be sufficiently representative for a long-term annual estimation of the PV-battery system performance. However, significant differences can be observed at monthly scale.

Highlights
- Months with similar irradiation and heating degree day can lead to largely different PV-battery system performance
- Differences in performance due to irradiation and temperature patterns are bigger when the size of the battery and PV surface are larger
- At annual level, these differences seem to be not impacting as observed in the monthly analysis
- TRY can be considered as representative only for long-term annual PV-battery system performance.

Introduction
The sustainable energy transition is one of the most important issues that the modern society must face in the upcoming decades. The path that must be followed includes a variety of solutions, which range from the implementation of clean energy production technologies to the enhancement of the efficiency of buildings and energy grids (Chel and Kaushik, 2018).

For what concerns modern and future buildings, the trend is to design low-energy structures, which can exploit the available renewable energy sources in the surrounding environment to satisfy their own energy demand (Simic et al., 2021). This creates the condition for a low-grid dependency on single-building or neighbourhood scale (Luo et al., 2023). Nearly zero-energy buildings (nZEBs) can fulfill the previously mentioned characteristics. In Europe, they represent nowadays a mandatory standard for both new and renovated buildings in most of EU Member States (European Parliament, 2010; Marszal et al., 2011).

Although several options are available, rooftop PV and solar thermal panels are the most applicable and feasible solutions for on-site generation of renewable energy for residential buildings (Torcellini et al., 2006), especially in urban areas where the installation of other kinds of systems can encounter difficulties (Tian et al., 2022). A typical configuration couples air-to-water heat pumps (AWHP) with PV panels to satisfy the building’s energy needs for space heating. However, even if heat pumps’ performances have strongly improved in recent years due to technology enhancements (IEA, 2022), there are still some issues to face to optimize the performance of the whole system, in particular regarding the mismatch between PV production and heating demand (Baggio et al., 2018). Many examples of solutions, aimed at facilitating on-site load matching, increasing self-consumption, reducing exchanges with the grid, and implementing peak shaving, rely on the installation of energy storage (Castillo-Cagigal et al., 2011a and 2011b; Brahman et al., 2015; Fischer, 2015; Prada et al., 2017), such as lithium batteries, water or latent heat mass storages.

Weather Data for Building Performance Simulation
Building Performance Simulation is a necessary tool to adopt in the design of high-performance buildings and for proper sizing of HVAC and energy storage systems, accounting for boundary conditions representative of the local climate (Attia et al., 2012). To make the calculated
building energy performance reliable, the current standard procedures require the adoption of the so-called “Test Reference Year” (TRY) as weather boundary conditions for the simulations (Adelard et al., 2000; Yang et al. 2008). Although many alternative methods are available in the literature, the approach most frequently adopted in Europe is described in the technical standard EN ISO 15927-4 (European Committee for Standardization, 2005) and is based on the method developed by Hall et al. (1978), which includes the Finkelstein-Schafer statistics (Finkelstein and Schafer, 1971).

According to the EN-ISO 15927-4 procedure, a TRY weather file is built starting from multi-year hourly series of actual weather variables, such as dry bulb temperature, relative humidity, global horizontal irradiation (GHI), and wind speed. Each TRY calendar month is the most representative among those present in the multi-year series. However, representativeness is assessed by means of the Finkelstein-Schafer (F-S) statistics in terms of cumulative distribution of daily quantities of weather variables, loosing in such a way the information regarding their hourly patterns as a selection criterion. Even if two months had the same F-S statistics for a given weather variable, they might be characterized by very different daily patterns (Figure 1).

![Figure 1: Two possible daily patterns for the same cumulative value of GHI](image1)

This difference could affect the assessment of actual behaviour and performance of HVAC systems, such as a PV-BESS with limited storage capacity. Indeed, in case of many consecutive sunny days (e.g., Figure 1B, days 8 to 11), the battery could be easily filled up and additional produced electricity had to be fed to the grid, while in case of consecutive overcast days (e.g., Figure 1B, days 4 to 7) the battery would get empty and electricity had to be imported. Quite the opposite, a more frequent alternation of sunny and overcast days (e.g., Figure 1A) could reduce the interaction with the grid.

Limitations of current TRY weather files are well known and documented in the literature, even if results are strongly dependent on local climatic conditions and specific applications (Bhandari et al., 2012; Pernigotto et al., 2014).

Aims of the research

Within the framework described in the previous sections, this research project considered a case study involving a terraced house equipped with an air-to-water heat pump fed by photovoltaic modules coupled with a battery storage. The aim of the study was to investigate how the hourly and daily pattern of weather variables affects the expected performance of the studied PV-BESS at monthly and annual levels. Having obtained this information, conclusions regarding the performance and suitability of TRY for the performance assessment of PV-BESS in this building system configuration could be drawn. Three cities belonging to very different climatic zones were considered: De Bilt, i.e., the location conventionally adopted to describe the whole Dutch climate conditions (Royal Netherlands Standardization Institute, 2018), Trento, an Italian Alpine city, and Padova, another Italian city in the Po valley.

Methods

Case-study and simulated configurations

As mentioned before, a single case study was chosen for the three analysed climates (De Bilt, Trento and Padova). Specifically, the selected semi-detached terraced house, with three floors of 52 m² each, is representative of the national house stock of the Netherlands (RVO – Netherlands Enterprise Agency, 2019). As regards the system, the house was equipped with an air-to-water heat pump, having a nominal COP=3, with radiators as emission units, a mechanical ventilation

<table>
<thead>
<tr>
<th>Table 1: Envelope properties for the different adopted configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP1</td>
</tr>
<tr>
<td>RC floor [m² K/W]</td>
</tr>
<tr>
<td>RC wall [m² K/W]</td>
</tr>
<tr>
<td>RC roof [m² K/W]</td>
</tr>
<tr>
<td>U windows [W/(m² K)]</td>
</tr>
<tr>
<td>Windows g value</td>
</tr>
<tr>
<td>Infiltration rate [dm³/m²]</td>
</tr>
</tbody>
</table>

Figure 2: Representation of case study building

Besides the case study geometry, represented in Figure 2, three different levels of insulation and infiltration rate were considered and analysed – RP1 (renovation package 1), RP3 and RP5, as shown in Table 1. Specifically, according to the Dutch NEN standards, RP1 fulfils the energy label B requirements, RP5 makes the house meet the Dutch Passive house standards while RP3 shows intermediate properties. Although Italian regulations are different, geometry and quality of the building envelope were kept the same also for Trento and Padova, in order to ensure comparability of the findings.
system with heat recovery, a 5 m² solar thermal collector for DHW purposes (Table 2), and a PV-BESS.

Table 2: Characteristics of solar thermal collector

<table>
<thead>
<tr>
<th>Solar collector area [m²]</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector fin efficiency factor</td>
<td>0.7</td>
</tr>
<tr>
<td>Absorber plate emittance</td>
<td>0.7</td>
</tr>
<tr>
<td>Absorptance of absorber plate</td>
<td>0.8</td>
</tr>
<tr>
<td>Bottom, edge loss coefficient [kJ/(hr m² K)]</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Two variants were considered for the PV system, with either 9 or 18 PV modules connected in series (Table 3), corresponding to configurations with half and whole south-oriented pitched roof covered with PV modules. Similarly, for each RP envelope configuration, 4 batteries capacities were simulated, including the case without battery (Table 4). A constant charge efficiency of 90 % was assumed for the battery. Efficiencies equal to 90 % and 96 % were set for PV-BESS regulator component and the AC/DC inverter, respectively.

Table 3: PV modules properties

<table>
<thead>
<tr>
<th>Mitsubishi Electric PV-MLU250HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells wired in series</td>
</tr>
<tr>
<td>Maximum power rating</td>
</tr>
<tr>
<td>Open circuit voltage (Voc)</td>
</tr>
<tr>
<td>Short circuit current (Isc)</td>
</tr>
<tr>
<td>Maximum power voltage (Vmp)</td>
</tr>
<tr>
<td>Maximum power current (Imp)</td>
</tr>
<tr>
<td>Module area</td>
</tr>
<tr>
<td>Temperature coefficient at Isc at ref. conditions</td>
</tr>
<tr>
<td>Temperature coefficient at Voc at ref. conditions</td>
</tr>
<tr>
<td>Module efficiency</td>
</tr>
</tbody>
</table>

Table 4: Battery sizes for different configurations

<table>
<thead>
<tr>
<th>Size 1</th>
<th>Size 2</th>
<th>Size 3</th>
<th>Size 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>[kWh]</td>
<td>[kWh]</td>
<td>[kWh]</td>
<td>[kWh]</td>
</tr>
<tr>
<td>RP1</td>
<td>0</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>RP3</td>
<td>0</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>RP5</td>
<td>0</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

As a first step, a TRNSYS model (Mohammadi et al., 2020) was properly set to run dynamic simulations and calculate the total electrical load. For each case, the heating system was preliminarily sized for all locations and RP configurations, considering an ideal heating system. Then, dynamic simulations were performed with the actual system to calculate the electrical load profiles for all configurations, using both multi-year series and TRYs as boundary conditions.

Weather data analysis

The three considered locations were characterized by weather data series of different length and properties. As regards De Bilt, The Netherlands, the input multi-year series ranged from 1996 to 2015. On the contrary, for Trento, Italy, years from 1986 to 2014 were used for both multi-year and TRY analyses – specifically, the available years included 1986-1988, 1990-1998, 2002, 2005-2007, 2009, 2012-2014 (Pernigotto et al., 2017 and 2020). Finally, for Padova, Italy, multi-year series ranged from 2008 to 2018. For all three locations, TRY weather files were developed according to the EN ISO 15927-4 procedure.

The analysis of multi-year and TRY weather data was performed at both monthly and annual timeframe. In particular, months were classified according to cumulative global horizontal irradiation and heating degree-days calculated with respect to a base temperature of 20 °C. Sequences of sunny and overcast days were also identified, considering the daily clear-sky index evaluated by means of the Solis-2017 model (Ineichen, 2008).

Parameters for the performance evaluation

The performances of the PV-BESSs were assessed through the On-site Energy Matching (OEM) and the On-site Energy Fraction (OEF) indices (Cao et al., 2013), which express how much the system can satisfy the building energy needs and store and make the produced energy ready to consume for the house.

OEM was calculated with the following equation:

OEM = Self Consumption [kWh] / On Site Generation [kWh]  

(1)

where On-Site Generation is the energy produced by the PV panels and Self Consumption (SC) represents the amount of on-site produced energy (either directly from PV panels or from battery storage) which is consumed by the building.

OEF, instead, was determined as follows:

OEF = Self Consumption [kWh] / Energy Demand [kWh]  

(2)

where the Energy Demand is the total electrical consumption.

Also in this case, the analysis was performed at both monthly and annual timeframe, comparing TRY results to similar months or years in the multi-year series.

Results

Monthly analysis of weather files and PV-BESS performances

As described before, weather data were analysed at both monthly and annual timeframe, comparing TRY representative months with those in the multi-year series sharing similarities. In many cases, months similar in terms of GHI and HDDs led to similar PV-BESS performances. Nevertheless, some months showed important differences.

An illustrative example is the case of April in De Bilt. In Figure 3, all April months from the entire multi-year series of weather data are represented, highlighting the TRY April, i.e., 2002 April, and the most similar one,
recorded in 2006. For sake of clarity, HDD and GHI values of these two months are reported also in Table 5.

**Figure 3: HDD-GHI chart for the April months in De Bilt**

<table>
<thead>
<tr>
<th>APRIL</th>
<th>HDD [K d]</th>
<th>GHI [kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRY (2002)</td>
<td>260</td>
<td>115.5</td>
</tr>
<tr>
<td>2006</td>
<td>270</td>
<td>113.3</td>
</tr>
</tbody>
</table>

As it is possible to observe, 2006 April was slightly colder and slightly more overcast than TRY April. Nevertheless, simulations underlined that PV-BESS performs better in 2006 April than in TRY April, as indicated for instance by OEF and OEM for the RP5 configurations reported in Figures 4 and 5, respectively without and with the largest considered battery. If no battery is installed, the performance points are very close to each other, while the performance difference is significantly larger in case of storage.

**Figure 4: Performance of the system in De Bilt with RP5, 18 modules and no battery**

**Figure 5: Performance of the system in De Bilt with RP5, 18 modules and 3 kWh battery**

The explanation for such performance difference can be found by analysing the daily profiles of the battery charge status and the distribution of daily GHI, HDD and clear-sky index values (Figures 6-9).

**Figure 6: State of Charge of RP5-18 modules-9 kWh configuration in case of TRY April (top) and 2006 April (bottom) in De Bilt**

**Figure 7: Daily values of GHI in case of TRY April (top) and 2006 April (bottom) in De Bilt**
Simulations run with TRY April showed that the battery remains completely full for a long series of days in the beginning of the month, as it is possible to see in Figure 6 (top). The extra produced energy in these days is sent into the grid, lowering the OEM value. The battery then gets discharged for a significant series of days in the middle of the month, as it happens again during the last days of April. When the battery is completely empty, the energy must be imported from the grid and at the same time the energy is not fed to the grid. More generally, the pattern of days with high and low irradiation is very different from TRY April and in 2006 there is a better alternation which improves the performance of the PV-BESS. Hence, even if the two months are similar in the cumulative values, the dissimilar patterns lead to different results in the performance evaluation.

The same method of analysis was adopted also for Trento and Padova. In Trento, as for De Bilt, most cases did not report significant differences in the estimated PV-BESS performances, especially in winter and summer seasons, while a couple of cases reported significant differences in the estimated PV-BESS performances, although TRY and multi-year months had similar GHI and HDD values. Specifically, the largest deviations were found in months at the end of the heating season (April and March), because of the largest variability encountered for both temperature and solar radiation patterns, affecting heating consumption and PV production. The largest differences between estimated PV-performance simulated with similar months was observed again in April with the RP5 configuration, 18 PV modules and 9 kWh battery. In particular, TRY April, i.e. 2004 April, 1993 April and 2002 April were taken in consideration. In Table 6, HDD and GHI values of the considered three months are reported.

### Table 6: HDD and GHI values for April months in Trento

<table>
<thead>
<tr>
<th>APRIL</th>
<th>HDD [K d]</th>
<th>GHI [kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRY (2004)</td>
<td>172.42</td>
<td>118.95</td>
</tr>
<tr>
<td>1993</td>
<td>172.88</td>
<td>113.15</td>
</tr>
<tr>
<td>2002</td>
<td>179.86</td>
<td>111.76</td>
</tr>
</tbody>
</table>

As represented in Figure 10, the difference in simulated system performance with April TRY and April 2002 is significant, especially in the OEM. Contrarily, the difference with April 1993 and April 2002 is non-significant. The same analysis on the temperature and irradiance pattern done for De Bilt was also carried out in
this case, highlighting how this can affect the performance of the PV-BESS system.

As for the Padova climate, only for the month of March there was a difference observed in the simulated performance of the PV-BESS system, while in all the other cases the pattern of HDD and GHI does not seem to be impacting.

Annual analysis of PV-BESS performances

After the monthly study, the analysis was then extended at annual level, with the goal to assess the PV-BESS long-term performance. Again, similar years were compared to look for substantial differences in the simulated performances. Figure 11 reports an example for RP5 buildings in De Bilt, analysing the total electrical consumption and the annual PV production.

Looking through all the PV-BESS configurations simulations results, the OEF and OEM values were compared. It was possible to notice that there are not substantial differences between TRY performances and the ones of any other similar year at annual scale, even if the reported ranges vary according to the number of PV modules and size of the battery. Although differences in predicted OEF-OEM increase with the size of the battery, they remain relatively small. As an example, Figure 12 reports the performances of the RP5 configuration with 18 PV modules and 15 kWh battery in De Bilt, which is one of those showing the largest differences between annual performances simulated with TRY and the most similar year. It is possible to observe how these points are very close, with negligible differences for both OEF and OEM.

To evaluate the representativeness of TRY for the PV-BESS performance estimation, the entire multi-year series was finally taken into analysis, calculating mean OEM and OEF values. Some statistics are indicated in Table 7 for the previously mentioned configuration (RP5-18 modules-9 kWh). It can be concluded that the TRY estimation of OEF and OEM is very close to the long-term average value of the entire multi-year series.

Figure 11: RP5 Electrical consumption and PV production for all the years of De Bilt

As for Trento and Padova, similar results were obtained as with De Bilt. The annual system performances simulated with TRYs as boundary conditions were similar to those obtained using similar years. Some statistics are indicated in Table 8 and Table 9 for the same configuration as before. Also in these locations, TRY estimation of PV-BESS performance is very close to the average value of the multi-year series.

Discussion

As a first general comment, it can be underlined that it is particularly important to use representative boundary conditions to get reliable predictions of the PV-battery system performance. Indeed, the very presence of a battery storage makes the trend of solar irradiation and temperature more relevant, since the charge/discharge cycles are greatly affected.

Studying the monthly behaviours of the various PV-battery system configurations, it was observed that the pattern of main physical quantities involved in the

![Figure 12: OEF-OEM for RP5-18 mod.-9 kWh with years similar to TRY in De Bilt](image)

### Table 7: Selected values of the annual performances with RP5-18 mod.-9 kWh in De Bilt

<table>
<thead>
<tr>
<th></th>
<th>OEF</th>
<th>OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-year average value [%]</td>
<td>51.69</td>
<td>60.91</td>
</tr>
<tr>
<td>Multi-year Standard dev. [%]</td>
<td>2.80</td>
<td>2.34</td>
</tr>
<tr>
<td>TRY value [%]</td>
<td>52.14</td>
<td>60.60</td>
</tr>
</tbody>
</table>

### Table 8: Selected values of the annual performances with RP5-18 mod.-9 kWh in Trento

<table>
<thead>
<tr>
<th></th>
<th>OEF</th>
<th>OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-year average value [%]</td>
<td>66.18</td>
<td>58.60</td>
</tr>
<tr>
<td>Multi-year Standard dev. [%]</td>
<td>3.66</td>
<td>3.19</td>
</tr>
<tr>
<td>TRY value [%]</td>
<td>66.00</td>
<td>58.03</td>
</tr>
</tbody>
</table>

### Table 9: Selected values of the annual performances with RP5-18 mod.-9 kWh in Padova

<table>
<thead>
<tr>
<th></th>
<th>OEF</th>
<th>OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-year average value [%]</td>
<td>67.62</td>
<td>50.45</td>
</tr>
<tr>
<td>Multi-year Standard dev. [%]</td>
<td>3.31</td>
<td>1.99</td>
</tr>
<tr>
<td>TRY value [%]</td>
<td>67.35</td>
<td>50.13</td>
</tr>
</tbody>
</table>
Particularly, it may be interesting:

- to repeat the analysis considering other definitions of Test Reference Year, for example the Typical Meteorological Year, which involves the Persistence Criterion.
- to assess the representativeness of TRY in case of smart controls and technologies installed in the building system.
- to incorporate variations in patterns within a given month for the purpose of typical annual performance assessment. The primary objective would be to avoid unintentional inclusion of anomalous sequences, rather than achieving the most average profile.
- to intentionally select anomalous sequences, in the context of sizing or testing performance under atypical conditions.
- to develop appropriate strategies for addressing atypical patterns, since these are expected to increase in frequency due to climate change.

**Conclusions**

In conclusion, the simulations performed for the locations of De Bilt, Trento and Padova suggest that the Finkelnstein-Schafer method used to generate TRY weather files, proposed by the international standards and commonly used in building performance simulation, can be suitable enough to assess the performance of PV-battery systems. In fact, representative results in terms of annual energy performance were obtained. Further analysis may be useful to investigate the irradiation and temperature pattern influence in other contexts. Particularly, it may be interesting:

- to consider other weather data related to different climates, especially Mediterranean ones.
- to include in the case study a cooling system in order to investigate the summer performance.

**References**


IEA (2022), Heat Pumps, IEA, Paris https://www.iea.org/reports/heat-pumps, License: CC BY 4.0


