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Review

Trigeneration for Italian University Campuses: A Thematic Review

Fabio Cardona * and Vamsi Sagiraju *

Department of Engineering, University of Palermo, Viale delle Scienze, Building 9, 90128 Palermo, Italy
* Correspondence: fabio.cardona@unipa.it (F.C.); vamsi.sagiraju@unipa.it (V.S.)

Abstract

University campuses are major energy consumers, necessitating innovative strategies to reduce grid load while protecting the environment. In Italy, climatic conditions vary substantially across the north, central, and southern regions. This thematic review assesses which claims about trigeneration (combined cooling, heating, and power) at Italian university campuses are supported by published institutional, climatic, and plant-level evidence, and which remain hypothetical. The evidence is analysed in three interconnected stages: (i) 2024 institutional electricity data and enrolment for five universities, compared using explicit accounting boundaries and harmonised to a lower-bound basis; (ii) heating and cooling degree days for their respective cities in 2023 and 2024, calculated from hourly temperature data and used solely as indicators of outdoor temperature exposure; and (iii) documented cogeneration and trigeneration installations at eight university sites, including the characteristics of eight prime-mover and system types. Reported electricity consumption in 2024 ranges from 25 to 47 GWh (average power 2.9 to 5.4 MW) on non-comparable boundaries; the four campuses with total or lower-bound figures fall between 36.6 and 47.2 GWh (4.2 to 5.4 MW). All five cities are heating-dominated; cooling degree days account for about 30% of total degree days in Rome and Naples, compared with 10% to 17% in Milan, Turin, and Padua. On-site generation accounts for 27 to 35 per cent of campus power where data are available. The most thoroughly documented options are reciprocating engines and microturbines, while the remaining technologies are primarily experimental. Because cost, hourly load, or emission statistics are unavailable, the technology assessment is a conditional, qualitative screening rather than an optimisation, and conclusions about the suitability of individual campuses are considered hypotheses.

Keywords: trigeneration; Italian universities; campus energy demand; sustainable energy innovation

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1. Introduction

Universities are often likened to towns or cities rather than merely places of study or work because they offer a wide range of facilities, including student residences, research centres, laboratories, academic buildings, and recreational amenities (e.g., restaurants, gyms, and cafeterias). These diverse activities have significant implications for energy efficiency [1,2]. Higher education institutions are miniature metropolitan systems with complex, simultaneous energy demands that differ from those of traditional commercial or residential structures. The Italian higher education system comprises 97 universities (69% state and 31% accredited non-state universities [3]). According to official statistics released by the Italian Ministry of University and Research (MUR) through its Ufficio di

Statistica (USTAT), the Italian university system comprises state and legally recognised non-state universities spread across the country. In the 2024/2025 academic year, total student enrolment surpassed 2.0 million, demonstrating the sector's long-term stability and scale amid demographic shifts. Over the last decade, annual new enrolments (immatricolati) have remained high, underscoring universities' structural relevance in Italy's socioeconomic system.

The demographic background for assessing energy use at Italian universities is given in Tables 1 and 2. While Table 2 shows student enrolment numbers for the chosen universities and campuses, including those examined in the energy consumption analysis and the documented cogeneration and trigeneration case studies, Table 1 shows the national scale and recent enrolment trends of the Italian higher education sector. While the recorded installations Section 7 include other institutions, such as the University of Siena, the University of Genova (Savona Campus), and the University Magna Graecia of Catanzaro, five universities are evaluated using their reported 2024 power usage figures Section 3 .

Table 1. Total number of enrolments in the last four years.

Year	Total Enrolled Students (Approx)	New Enrolments (Approx)
2021–2022	~1.85 million	~315,000
2022–2023	~1.90 million	~329,817
2023–2024	~1.95 million	~335,000
2024–2025	>2.0 million	~340,000

Source: Official statistics released by the Italian Ministry of University and Research (MUR) through its Ufficio di Statistica (USTAT).

Table 2. Student enrolment, annual new enrolments, and inclusion of selected Italian universities in the energy and trigeneration analyses.

University	City	Total Enrolled Students (Approx)	Annual New Enrolments	In Energy Comparison (Section 3)	In Installation Review (Section 7)
Sapienza University of Rome	Rome	112,000	21,000	Yes	Yes
University of Turin	Turin	77,000	15,000	Yes	Yes
University of Naples Federico II	Naples	71,170	14,000	Yes	No
University of Padua	Padua	70,786	13,800	Yes	No
Politecnico di Milano	Milan	47,700	9500	Yes	Yes
University of Palermo	Palermo	43,650	8900	No	Yes
Politecnico di Torino	Turin	34,000	7200	No	Yes
University of Siena	Siena	14,833	2369	No (2024 figure used only to scale the forecast)	Yes
University of Genova	Genova	31,976	5938	No	Yes
University Magna Graecia of Catanzaro	Catanzaro	12,056	2016	No	Yes

Source: Table compilation based on official student enrolment statistics published by the Italian Ministry of University and Research (MUR), Servizio Statistico (USTAT).

Campus energy use is expected to depend on student numbers, as well as on laboratories, residences, health-care buildings, and operating hours [4,5]. In central and southern Italy, where summer temperatures are rising and comfort demands are increasing, electricity consumption for cooling has risen sharply in recent years [6]. As a result, universities are now under pressure to reduce greenhouse gas emissions in line with EU energy and climate policy while also facing rising operating costs.

In this context, trigeneration systems, also known as combined cooling, heating, and power (CCHP), can offer universities an energy alternative. Trigeneration simultaneously generates electricity, useful heat, and cooling from a single primary energy source, leading to higher overall efficiency than separate conventional generation [7]. University campuses may be especially well suited to trigeneration where electrical, heating, and cooling demands coincide; Section 7 shows that the available data cannot verify this coincidence. Universities can also serve as living labs, supporting applied research, teaching on sustainable energy systems, and technical innovation. Much of the research is scattered: it consists of single-case studies or generic techno-economic analyses, with little attention to governance and national adoption trends.

Accordingly, this thematic review examines what the published evidence can and cannot say about the potential of trigeneration systems in Italian universities. The study looks at:

- Comparison of the Italian universities' energy demand,
- University campuses using trigeneration technologies,
- Trigeneration technologies: characteristics and university applications.

The review addresses one research question: which statements about trigeneration's suitability for Italian university campuses are supported by published institutional, climatic, and plant-level evidence, and which can only be expressed as hypotheses because load data are lacking? Section 2.3 illustrates how the three topics mentioned above relate to answering this question. By integrating official data with current research, the paper intends to help Italy's higher education sector make evidence-based decisions about implementing trigeneration systems.

Existing reviews of trigeneration classify prime movers, cooling technologies and operating strategies for buildings and industry in general, and reviews of campus energy [1,2] focus on demand modelling and management. To our knowledge, no review has compared reported energy data from Italian universities, the climate exposure of their cities, and documented cogeneration and trigeneration installations on a common basis. This review contributes: (i) a 2024 comparison of institutional electricity data with explicit accounting boundaries (Section 3); (ii) heating and cooling degree days calculated in the same way for five university cities (Section 4); (iii) a consolidated table of documented plants that separates measured, estimated, forecast and supplier-reported values (Section 7.4); (iv) an evidence-graded screening of eight technologies (Section 7.4); and (v) the features that are specific to university campuses (Section 7.6) and the data needed for economic and environmental assessment. By integrating official data with current research, the paper aims to support evidence-based screening of trigeneration options in Italy's higher education sector.

2. Methodology

This paper used the thematic approach described by [8] to conduct the review. A thematic literature review evaluated the potential for studying the trigeneration systems in Italian universities by analysing campus location, student enrolment, reported energy consumption, and climatic conditions. This methodology was selected because the available evidence is diverse, including reports, energy consumption data, statistical databases, and scientific studies on cogeneration and trigeneration. Differences in reporting periods, system

boundaries, technical specifications, and performance indicators restrict direct quantitative comparisons between cases.

The review integrates descriptive quantitative analysis of institutional and technical data with thematic synthesis of published research to clarify the primary contribution. The aim is to identify relationships among university characteristics, temperature conditions, energy requirements, and the technical features of trigeneration systems, while differentiating documented performance from potential applications.

2.1. Review Approach

The review revolves around three interrelated research themes:

- Energy characteristics of Italian universities: An examination of reported electricity usage, available thermal energy information, student enrolment, geographic location, and the universities' energy accounting limits.
- Documented university cogeneration and trigeneration systems: Examined existing installations, including prime movers, nominal electrical and thermal capacities, cooling configurations, and reported energy generation.
- Technical applicability of trigeneration technologies: A comparison of the operational characteristics of various prime movers and integrated configurations, with a focus on campus energy requirements and seasonal heating and cooling conditions.

2.2. Data Sources and Literature Selection

The review depends on two categories of sources:

- Institutional and statistical sources: University enrolment, reported energy consumption, and current energy infrastructure are described using the official publications of the Italian Ministry of University and Research (MUR), institutional sustainability reports, university energy statements, and associated technical data. These sources provide the main material used to compare the selected Italian institutions.
- Scientific and technical literature: Peer-reviewed journal articles, conference papers, and relevant technical publications are used to examine trigeneration technologies, their operating characteristics, documented applications, and reported technical, economic, and environmental performance; they are collected from journals and websites like Scopus, ScienceDirect, Google Scholar, ResearchGate, and IEEE Xplore.

We preferred 2024 for the institutional comparison where a suitable figure was available. Purchased electricity, generated electricity and fuel input were not combined or compared as equivalent measures of useful energy. We treated missing information on residences, laboratories, and district heating coverage as a limitation of the evidence. We synthesised the evidence by comparing it within and across these themes and identifying where the available observations support, qualify, or contradict a proposed application. We therefore interpret technology recommendations as conditional screening outcomes. Because most institutional reports do not provide harmonised hourly electricity, heating and cooling load profiles, this review does not claim to establish optimised plant capacities, measured climate-driven changes in campus cooling demand or verified economic payback for the selected universities.

We searched Scopus, ScienceDirect, Google Scholar, ResearchGate, and IEEE Xplore between 2000 and 2025 using the following strings: "trigeneration" OR "CCHP" OR "trigeneration" AND "university" OR "campus", "operating characteristics" and "fundamental principles". We found institutional reports on university websites. We used a thematic review approach, not a systematic review approach. We did not keep a search log: the number of records identified and screened, or the records excluded, so we cannot provide

a flow diagram or reproduce the selection exactly. We therefore make no claim that the review is exhaustive.

The reviewed bibliography comprises 53 references. The literature selection criteria focus on studies addressing university campus energy consumption and demand characteristics, existing cogeneration, trigeneration, and polygeneration applications, and the technical, economic, and environmental performance of relevant energy conversion technologies. All cases are Italian university campuses and therefore share the same national regulatory and incentive framework; climate and building typology differ between cities and are examined in Sections 4 and 7.3. The energy comparison sample (five universities) and the installation sample (eight sites) overlap only partly, as explained in Section 2.3.

Sources that publish recognisable system specs, generating capacity, energy outputs, and operational conditions are given precedence for quantitative comparison. Quantitative evaluation excludes duplicate publications, studies unrelated to the study aims, and sources with unverifiable technical information. Studies with low numerical data but relevant conceptual or technological information may be kept for qualitative discussion.

The chosen literature comprises three topic groups: documented campus cogeneration and trigeneration installations, university energy characteristics, and the correlation between climate conditions and technological suitability.

2.3. Selection of Cases and Analytical Logic

The campuses were selected in two steps. First, the energy comparison (Section 3) includes five universities with publicly available institutional reports providing annual electricity consumption for the calendar year of 2024: Politecnico di Milano, Turin, Sapienza, Naples Federico II and Padua. Together, these institutions cover northern, central and southern Italy. Second, the installation review (Sections 5 and 6) includes all Italian university sites identified in the reviewed literature or institutional sources as having a cogeneration or trigeneration plant, irrespective of the availability of comparable 2024 electricity data. This sample additionally includes Siena, Genova (Savona), Catanzaro, Palermo and Politecnico di Torino.

Politecnico di Milano, Turin and Sapienza appear in both samples. Naples Federico II and Padua have comparable electricity data, but no plant was documented in the sources reviewed. The remaining sites have documented plants but lack comparable 2024 electricity statements; Siena's 2024 electricity figure is used only to scale the forecast output of its new plant (Section 5.4). Table 2 identifies the overlap between the samples, while reports degree days for the five cities included in the energy comparison. Selection depended on public reporting; consequently, the samples are not statistically representative of the Italian university system, and the findings are not extrapolated to that system.

The analysis follows five stages, linking the three research themes to specific subquestions:

- Scale (Section 3): What is the order of magnitude of average electrical load after reported consumption is placed on a harmonised, lower-bound basis?
- Climate exposure (Sections 4 and 7): How do heating and cooling degree days, used as indicators of outdoor temperature exposure, vary across the five cities and between 2023 and 2024?
- Installed base (Section 7): Which university cogeneration and trigeneration plants are documented, and what do measured, estimated, forecast, and supplier-reported data indicate about their operation or expected performance?
- Technology fit (Section 7): Which prime movers and configurations have documented university applications, and what constraints limit their use?

- Synthesis (Section 7): Which conclusions are supported by the available evidence (S), which remain hypotheses requiring load-profile data (H), and which cannot be assessed with the available data (X)?

These stages inform an evidence-qualified synthesis rather than a campus-specific suitability index. Each conclusion is classified as supported (S), consistent with the evidence but untested (H), or not assessable with the available data (X).

3. Comparison of Italian Universities' Energy Demand

We used institutional energy-consumption statements and sustainability reports to obtain annual energy indicators. We documented energy flows, including externally provided district heat, natural gas used as fuel, on-site electricity generation, and grid electricity purchases. When explicit values were available, we chose calendar year 2024 as the preferred reporting period. We kept the scope-restricted indicators and older data but did not rename them, as the entire campus needs to be reported for 2024. Reported totals are considered directly comparable only when building inventories, geographic coverage, and energy-carrier criteria coincide.

University campuses include teaching facilities, research laboratories, administrative buildings and, in some cases, student accommodation and health-care facilities. Differences in overall power use cannot be attributed solely to variations in operational efficiency or climate sensitivity because institutional limits differ. Information is reported as not established rather than assumed when sources do not specifically state residence coverage, campus floor space, or on-site production.

Table 3 shows the common reporting year and the available accounting definitions. Before comparing institutions, consider variations in electricity accounting, building coverage, and separately reported thermal or fuel use. The next subsections discuss each institution based on its own reporting records; hourly electrical, heating, and cooling loads are not inferred from annual totals.

Because the reported values do not share a single boundary, they are harmonised in three phases with no additional estimated data. Step 1: Each figure is allocated to a basis class based on its source information. Class A represents entire institutional energy consumption as reported (Turin; Naples Federico II, whose composition is not itemised in the report), class B represents grid power purchased exclusively (Sapienza, Padua), and class C represents a partial end-use figure (Politecnico di Milano). Step 2: For class B, documented on-site electricity generation is added to grid purchases to provide a lower bound for total use: 37.527 GWh for Sapienza (37.522 GWh purchased plus approximately 0.005 GWh of photovoltaic output) and 40.896 GWh for Padua (40.793 GWh purchased plus 0.103 GWh of renewable electricity). Neither university publishes on-site cogeneration production; hence, these figures stay lower. Step 3: Class C is removed from the comparison band, and Politecnico di Milano is represented by its stated partial value and, separately, the institution's anticipated total of 40 to 45 GWh per year, which is an estimate rather than a measurement. Missing loads are not extrapolated.

Table 3. Electricity consumption reported by selected Italian universities in 2024, with accounting definitions and boundary information. Class A: total institutional user; Class B: grid purchases only; Class C: partial end-use.

S.NO	University	Electricity Consumption [GWh/y]	Reference Year	Location	Report Electricity Accounting Basis	Enrolled Students	Electricity per Student [kWh/Student]	Basis Class and Harmonised (Lower-Bound) Comparison
1	Politecnico di Milano	25.374025	2024	North	Electricity that does not include student housing or climate-control loads	47,700	532	Class C. Partial end-use figure; excluded from the harmonised band. Estimated total 40–45 GWh/y (4.6–5.1 MW), not a measured value.
2	University of Turin	36.641616	2024	West	Total institutional power: bought electricity + CHP + PV 2024	77,000	476	Class A. Total institutional use as reported (grid + CHP + PV). Lower bound 36.64 GWh/y (4.17 MW); residential coverage not provided.
3	Sapienza Università di Roma	37.522398	2024	Central	Grid electricity purchased at university supply points	112,000	335	Class B. Grid purchases only; adding about 0.005 GWh of PV gives a lower bound of 37.53 GWh/y (4.27 MW). Does not include all on-campus purchases or CHP output.
4	University of Naples Federico II	47.216	2024	South	Institutional electricity consumption	71,170	663	Class A. Institutional electricity as reported, 47.216 GWh/y (5.38 MW); composition not itemised and no building-level demand data
5	University of Padua	40.7931	2024	East	Grid electricity purchased	70,786	576	Class B. Grid purchases only; adding 0.103 GWh of renewable electricity gives a lower bound of 40.90 GWh/y (4.66 MW)—no building-level data.

Source: Institutional energy and sustainability reports of the selected universities [9–15]. Students: Table 2 MUR values or the university's own report where stated; kWh per student = reported annual electricity / students.

On this assumption, the four campuses of classes A and B fall between 36.6 GWh (Turin) and 47.2 GWh (Naples Federico II) in 2024, corresponding to average electrical outputs of 4.2 to 5.4 MW, with Politecnico di Milano's predicted total (4.6 to 5.1 MW) falling within this range. The harmonised numbers continue to reflect solely yearly energy; they make no mention of peak demand, load shape, or thermal demand, and the class B values are lower boundaries rather than totals. The indicated range of 25 to 47 GWh (2.9 to 5.4 MW) is retained in Table 3, but it should not be interpreted as the average scale of campus loads because the lower end is a partial measure. Per-student indicators are added to Table 3, using enrolment as reported by each university where available (Naples, Padua) and the approximate MUR values of Table 2 for the others. They range from about 335 kWh per student (Sapienza, grid purchases only) to 663 kWh per student (Naples Federico II, total institutional electricity). Their order does not follow the basis classes: Politecnico di Milano reports a partial figure but exceeds Turin's total-use value (532 against 476 kWh per student). Enrolment therefore does not explain the spread, as expected for a variable that ignores floor area, laboratory intensity, residences and clinical facilities (Section 1). Per-student values are reported as normalised descriptors and are not used to rank campuses or to size plants.

3.1. Politecnico Di Milano

Milan, the energetic capital of Lombardy in Italy's Po Valley, is home to Politecnico di Milano, Italy's top technical university. The city has a humid subtropical climate with hot, humid summers and cold, foggy winters.

After excluding power used for student housing and temperature control, Politecnico di Milano reported 25.374025 GWh of electricity use in its 2024 institutional performance report [9,10], down from 26.725440 GWh in 2023. For this well-defined metric, the decrease was 5.06%. This partial end-use figure is not appropriate for interpreting the institution's total electricity demand. Separately, institutional energy-management records state that the institution needs an estimated 40–45 GWh of power per year, although they do not specify that range as the measured total for 2024. In 2024, the institution reported solar production exceeding 0.900 GWh [9,10].

The Figure 1 above show overall electricity consumption over the last three years. The university itself has a trigeneration plant and a solar plant to reduce CO2 emissions and increase sustainability.

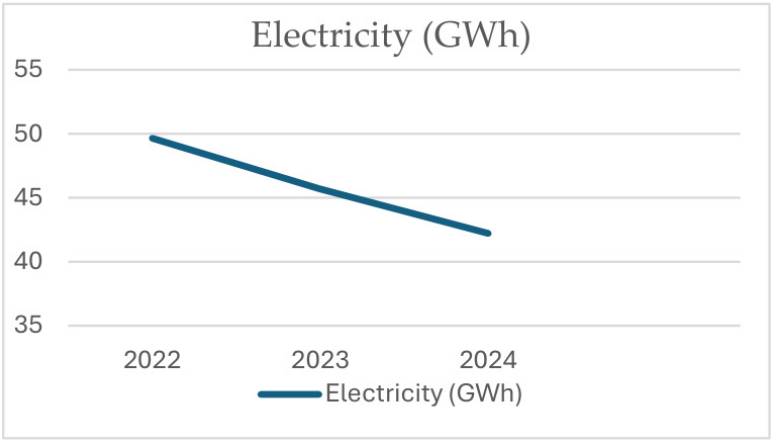


Figure 1. Electricity consumption of Politecnico di Milano, 2022–2024. Source: Politecnico di Milano energy consumption data from the last three years, sourced from Piano Strategico di Sostenibilità 2023–2025: Aggiornamento 2025 e Rapporto di Sostenibilità 2024 [10].

3.2. University of Turin

The University of Turin (Università degli Studi di Torino, UniTo) is located in Turin (Torino), Piedmont, in western Italy, near the Alpine arc and in the Po Valley. This urban city makes hotter summers and milder winters more significant for campus energy consumption.

The University of Turin used 36.641616 GWh of power in 2024: 0.102037 GWh from photovoltaics, 12.887195 GWh from three on-site cogeneration units, and 23.652384 GWh from the grid [11]. District heating was recorded separately at 16.902035 GWh, while annual natural gas use was 2,783,264 m^3. The electrical balance specifically includes lighting, winter and summer air conditioning, and energy-intensive labs [12]. During the 8784 h leap year, the average electrical consumption was 4.171 MW. The organisation runs three 1.3 MWe Otto-cycle reciprocating engine units. If all three of these units were available throughout 2024, their total electrical full-load-equivalent hours would have been 12,887.195 MWh/ 3.9 MW = 3304 h, or a 37.6% calendar-year capacity factor. A total of 35.17% of reported yearly power consumption came from on-site CHP generation; this is a generation fraction rather than an independently measured self-consumption fraction.

3.3. Sapienza Università Di Roma

The main campus of Sapienza Università di Roma is in Rome's San Lorenzo area, in the Lazio region of central Italy. According to the 2024 annual consumption report, the university purchased 2,439,375 Sm^3 of natural gas and 37.522398 GWh of electricity from around 81 grid supply points. The average power purchased was 4.272 MW over 8784 h. Because the same dataset [13] does not provide the precise portfolio of individually metered facilities or the contribution of all on-site generation, the yearly grid-import total cannot be regarded as total electrical demand.

The university's yearly electrical balance details grid electricity that was purchased, but it does not include a separately reconciled 2024 output for the Ortopedia and Regina Elena CHP plans or the reported microturbine research setup. As a result, the equipment specifications listed in previous technical documents are considered installation/project descriptions and are not associated with 2024 power production. The 2024 institutional energy report (Table 4, [13]) includes a separate report on the photovoltaic production of around 0.005 GWh.

Table 4. Yearly energy consumption of the Sapienza University campus.

Year	Natural Gas Consumption (Sm^3)	Grid Electricity Consumption (MWh)
2017	1,967,551	33,833.444
2018	1,884,551	34,169.573
2019	1,762,912	37,451.985
2020	1,518,111	29,509.203
2021	2,033,851	33,306.413
2022	1,791,987	36,785.789
2023	1,624,786	36,886.860
2024	2,439,375	37,522.398

Source: Sapienza Università di Roma. Rapporto Annuale dei Consumi 2024. Data were collected and tabulated from this reference [13].

3.4. University of Naples Federico II

Situated in southern Italy, it is one of the oldest universities and is located in Naples. The University of Naples Federico II reported 47.216 GWh of electricity consumption and 12.439 GWh of natural-gas energy in 2024, totalling 59.655 GWh for these final-energy carriers. The institution also reported 71,170 enrolled students and annual electricity and gas expenditures of approximately EUR 10.820 million and EUR 0.754 million, respectively, in its 2025 sustainability report [14]. The 2024 annual-average electrical power equivalent is 5.375 MW (47,216 MWh/8784 h). The 2024 electricity-to-student ratio is approximately 663.4 kWh per reported student.

3.5. University of Padua

The University of Padua is in the humid Po Valley climate in eastern Italy. Summers are hot and humid, and winters are cool and foggy. As a result, year-to-year temperature changes usually increase summer electricity use for cooling and decrease winter space-heating fuel use. The University of Padua's Rapporto di Sostenibilità 2024–2025 explicitly defines the reporting period as calendar year 2024 and academic year 2024/2025 [15]. The primary energy table reports 40,793.1 MWh of grid electricity, 102.9 MWh of renewable electricity, 2352,715 Sm^3 of natural gas, and 220.8 MWh of heat from a thermal carrier for 2024. A separate total-energy indicator is provided as 9710.90 tonnes of oil equivalent (toe); this value aggregates multiple energy carriers and should not be combined with the electrical quantities. Grid electricity increased by 3.05% from 39,586.3 MWh in 2023, while natural gas consumption decreased by 8.35% from 2,567,153 Sm^3. The report presents normalised natural-gas use of 2,874,887 Sm^3 in 2023 and 2,816,500 Sm^3 in 2024, representing a 2.03% decline after weather adjustment. This adjustment shows that climate variability affects how we interpret fuel-consumption trends. The university reports 70,786 students and an estate comprising 165 buildings and sites covering over 606,566 m^2, but does not specify the precise overlap between the estate inventory and the metered utility boundary. The report calculates a 2024 annual-average grid import of 4.644 MW and grid electricity per reported student of approximately 576.3 kWh/student. Neither metric reflects maximum demand or total campus electrical use. The report lacks sufficient detail on heating and cooling delivery profiles to quantify useful thermal demand or to determine trigeneration sizing.

According to the primary 2024 table [15], year-on-year changes include a 3.05% increase in grid electricity, a 3.63% increase in renewable electricity, a 5.65% increase in thermal-carrier heat, and a 0.53% increase in total energy measured in tonnes of oil equivalent. The report also gives the report-level intensity as 0.127 toe per student, based on the university's definition. These values serve as descriptive indicators and do not quantify observed trigeneration energy savings.

The reported renewable-electricity production of 0.1029 GWh is separate from the 40.7931 GWh purchased from the electricity grid. The sustainability report also details newly installed photovoltaic equipment in 2024; however, installed peak capacity should not be interpreted as equivalent to full-year measured generation. The primary 2024 energy table [15] does not identify any separately measured electrical output from cogeneration or trigeneration.

4. Comparative Analysis of Heating and Cooling Degree Days in Italian University Locations

We examined five university cities from north to south, using outdoor temperature data from 2023 and 2024. The Open-Meteo Historical Weather API provided hourly outdoor temperature data for Milan, Turin, Rome, Naples, and Padua for the years 2023–2024 [16]. We then used Eurostat's approach [17] to calculate heating degree days (HDDs) and cooling

degree days (CDDs). Temperature-based screening indicators include heating degree days (HDDs) and cooling degree days (CDDs). They do not account for measured usable thermal loads, humidity, building-envelope performance, laboratory demand, campus working schedules, or cooling-system efficiency.

Heating degree days (HDD_d) [17]:

$$HDD_d = \begin{cases} 18 - T_d, & T_d \leq 15\,^0C \\ 0, & T_d > 15\,^0C \end{cases} \quad (1)$$

Cooling degree days (CDD_d):

$$CDD_d = \begin{cases} T_d - 21, & T_d \geq 24\,^0C \\ 0, & T_d < 24\,^0C \end{cases} \quad (2)$$

Here, T_d is the daily mean outdoor temperature, calculated from the 24-hourly observations. Annual HDD and CDD are the sums of their daily values.

For example, a day averaging 12 °C contributes 6 heating degree days. A day averaging 26 °C contributes 5 cooling degree days.

The comparison covers only two calendar years. Differences between 2023 and 2024 therefore describe inter-annual variability in those years and not a climate trend, and two years are not sufficient to characterise the long-term climate of any city, which would require multi-decade normals. HDDs and CDDs describe outdoor temperature only. Building heating and cooling loads additionally depend on envelope performance, building function, occupancy schedules, internal gains and the efficiency and operation of HVAC systems, none of which is available at campus level here. HDDs and CDDs are used in Sections 4 and 7.3 solely as comparative exposure indicators, and the cooling share of total degree days, CDD/(HDD + CDD), is used as a descriptor of relative exposure and not as an estimate of demand Table 5.

Table 5. Climate indicators for university cities derived from hourly Open-Meteo temperature data. Calculation carried out using Equations (1) and (2) (2023–2024).

City	HDD 2023	HDD 2024	ΔHDD [%]	CDD 2023	CDD 2024	ΔCDD [%]
Milan	1886.7	1951.0	+3.4	271.3	280.3	+3.3
Turin	2191.2	2276.4	+3.9	236.4	250.6	+6.0
Rome	1269.3	1189.7	−6.3	421.1	551.4	+30.9
Naples	1087.4	1039.2	−4.4	342.2	443.4	+29.6
Padua	1926.6	1879.9	−2.4	272.3	377.3	+38.6

Source and definitions: The authors used Eurostat degree-day thresholds (HDD: 15 °C activation/18 °C reference; CDD: 24 °C activation/21 °C reference) to calculate the five Open-Meteo archived hourly temperature exports. Calendar days correspond to the GMT time stamps in the source files. The percentage change from 2023 to 2024 is shown by Δ. HDD and CDD are expressed in °C days [17].

5. University Campuses Using Trigeneration Technologies

In the previous section, this paper discussed about different universities' energy consumption. This section discusses campuses with trigeneration and other renewable plants in detail. It also discusses the type of prime mover used and the annual amount of energy generated were tabulated in the below Table 6.

Table 6. Technical and operational characteristics of cogeneration and trigeneration systems installed at Italian university campuses.

University	Technology	Rated Electrical Output [MWe/kWe]	Thermal/Cooling Information
Politecnico di Milano	Natural gas Reciprocating engine	2 MWe	Heat recovery via engine circuits; absorption cooling approximately 1.4 MWc
University of Turin	Three Otto-cycle engines	3 × 1.3 MWe	Palazzo Nuovo: ~1.4 MWth/ 1.0 MWc
Sapienza Università di Roma	Two Gas microturbine/ One Endothermic engine	100 kWe 580 kWe 250 kWe	Nominal ~167 kWth heat recovery; absorption configuration described in technical sources; 670 kWth recovered
University of Siena	Recently installed trigeneration	531 kWe	Forecast heat 1.8 GWh/y; forecast cooling 1.4 GWh/y

Source: Institutional energy and sustainability reports of the selected universities [9–19].

5.1. Politecnico Di Milano

The Leonardo–Bassini–Bonardi PoliGrid employs a natural-gas reciprocating engine (Jenbacher JMS 612) with a rated electrical output of approximately 2 MW. It uses heat recovery for district heating, and an absorption cooling system enables trigeneration during the cooling season. The university reports an installed absorption-cooling capacity of approximately 1.4 MW. These values represent installed equipment capacities, not measured annual energy delivery.

The university's Bilancio Energetico di Ateneo (BEA) 2020 Executive Summary indicates that the cogenerator produced approximately 12 GWh of electricity in 2020, with about 11 GWh self-consumed and 1 GWh exported to the public grid. Dividing the reported output by the 2 MW rated electrical capacity yields about 6000 electrical equivalent full-load hours. The annual electrical self-consumption fraction is estimated at 91.7%. Both results are based on approximate, historical BEA data and should be interpreted with corresponding precision.

For 2024, the institutional performance report indicates 25.374025 GWh for an electricity-consumption metric that excludes air-conditioning and residential consumption. The energy-management website separately records over 0.900 GWh of photovoltaic generation for the same year. In detailed PoliGrid installed specifications and documented generation are tabluated in the below Table 7.

Table 7. PoliGrid installed specifications, documented generation and electricity reporting.

Quantity	Reported/ Calculated Value	Evidence and Interpretation
Installed electrical capacity [MWe]	2	PoliGrid installed reciprocating engine
Installed absorption cooling capacity [MWc]	≈1.4	Rated capacity, not annual cooling generation
Cogeneration electricity [GWh]	≈12	BEA 2020; approximate annual generation
Used internally/exported [GWh]	≈11/≈1	BEA 2020 electricity balance
Electrical equivalent full-load hours [h]	≈6000 h	12,000 MWh/2 MW Derived
Electricity self-consumption fraction [%]	≈91.7	11/12 derived from approximate values

Table 7. *Cont.*

Quantity	Reported/ Calculated Value	Evidence and Interpretation
Electricity excluding cooling and residences [GWh]	25.374025	Reported in the 2024 energy indicator
PV electricity generation [GWh]	>0.900	Institutional PV data

Source: Politecnico di Milano. Piano Strategico di Sostenibilità 2023–2025: Aggiornamento 2025 e Rapporto di Sostenibilità 2024. Data were collected and tabulated from these references [9,10].

5.2. University of Turin

In 2024, the University of Turin consumed 23.65 GWh of grid electricity, generated 12.89 GWh through cogeneration, and produced 0.10 GWh from solar panels [11]. The university operates three Otto-cycle units with a combined nominal electrical capacity of 3.9 MWe. Assuming this capacity is fully available throughout 2024, the estimated annual capacity factor is 37.6%. The fleet-level equivalent full-load hours are approximately 3304 (12,887.195 MWh divided by 3.9 MW).

Location-level records show energy recovered from cogeneration alongside heating supplies. In 2024, heating supply at two sites totalled 3789.2 MWh and 7594.5 MWh, with recovered heat at Palazzo Nuovo and Grugliasco about 2400.5 MWh and 2510.8 MWh, respectively.

5.3. Sapienza Università Di Roma

In its annual report, UniRo have three different trigeneration and cogeneration plants in different campuses that combine an on-site generation strategy with a trigeneration configuration: an exhaust gas-driven absorption chiller, a gas microturbine producing 100 kW with a nominal electrical efficiency of 30%, and heat recovery of approximately 167 kW through a flue-gas/water heat exchanger. This enables simultaneous production of electricity, useful heat, and cooling. At other campuses, they generate 580 kW and 250 kW in cogeneration and 670 kW in energy recovery Table 8 [13].

According to Sapienza Università di Roma's Annual Energy Consumption Report 2024, the institution bought about 37.522398 GWh of power from the grid. In the same year, seven operational solar systems produced around 5000 kWh of power. The report does not mention thermal recovery at the Regina Elena Complex.

Table 8. Trigeneration system specification at Sapienza University of Rome.

Generation Plant	System Type	Electrical Output [kW]	Thermal Recovery [kW]
Trigeneration System	Trigeneration (CHP + absorption)	100	167
Ortopedia building	Cogeneration (CHP)	580	670
Regina Elena complex	Cogeneration (CHP) + new chiller plant	250	Not Recorded

Source: Sapienza Università di Roma's Annual Energy Consumption Report 2024. Data were collected and tabulated from this reference [13]. The thermal recovery for the third plant is not recorded in the source data.

5.4. University of Siena

To increase sustainability on the university campus, UniSi installed a high-efficiency trigeneration plant in December 2025 at Polo Scientific di San Miniato, with 531 kWe electricity capacity, as part of an energy renovation project. Since it is a new plant, less than a year old, it has no annual data to compare generation and production. However, UniSi stated that the plant is expected to generate approximately 3 GWh of electricity, 1.8 GWh of

useful heat energy, and 1.4 GWh of cooling energy per year. According to [18,19], UniSi consumes 8.64 GWh of electricity, and the forecast annual generation is equivalent to 34.7% of the university's reported 2024 electricity consumption.

Calculation of Generation share:

$$Generation\ share = \frac{E_{forecast}}{E_{university,2024}} \times 100 \quad (3)$$

$$Generation\ share = \frac{3,000,000}{8,641,707} \times 100$$

Here, solving the equation shows that the 34.7% consumption figure refers to the university-wide accounting boundary, and the projected production relates to the San Miniato facility; this percentage represents a theoretical generation-to-consumption comparison rather than measured electricity savings or verified demand coverage. Actual operational data are needed to determine electricity self-consumption and savings.

6. Trigeneration Technologies: Characteristics and University Applications

Trigeneration is one of the most promising technologies, allowing the efficient simultaneous production of heat, cooling, and power, with potential technical, economic, and environmental benefits [20]. It is known as combined cooling, heating and power (CCHP). In a trigeneration plant, waste energy from a generation unit, such as a gas turbine, drives both the heating and cooling systems [21]. This section discusses different types of trigeneration plants used across campuses and commercial spaces, from traditional to modern plants.

6.1. Internal Combustion Engine (ICE)

Internal combustion engines (ICEs) have been a traditional CHP and CCHP technology for decades. Reciprocating internal combustion engines [22] are primarily categorised into compression–ignition (Diesel) engines and spark–ignition (Otto) engines. In terms of performance, reciprocating engines typically have electrical efficiencies of 25% to 45%, depending on size and design. These range from 10 kW to 10 MW. Fuels can be fossil fuels, natural gas or biogas Figure 2.

At Politecnico di Torino in Italy, they installed an automotive-derived, natural gas-fired reciprocating internal combustion engine (ICE) Figure 3 [23]. This plant is an innovative, small-scale CCHP system integrated with a liquid desiccant cooling system. Specifically, an Otto four-stroke model with a displacement of 5883 cm3. This engine is coupled with an asynchronous, water-cooled generator and a power electronic unit (AC/DC–DC/AC converter) that enables variable-speed operation, ensuring high efficiency even at partial loads. The unit also includes a three-way catalytic converter to ensure low pollutant emissions. This plant has an electrical capacity of 126 kW, a thermal capacity of 220 kW, a cooling capacity of 210 kW, a liquid LiCl–water desiccant conditioner capacity of 168 kW, and a rotary heat exchanger capacity of 42 kW. This system treats fresh air with a nominal capacity of 20,000 m^3/h.

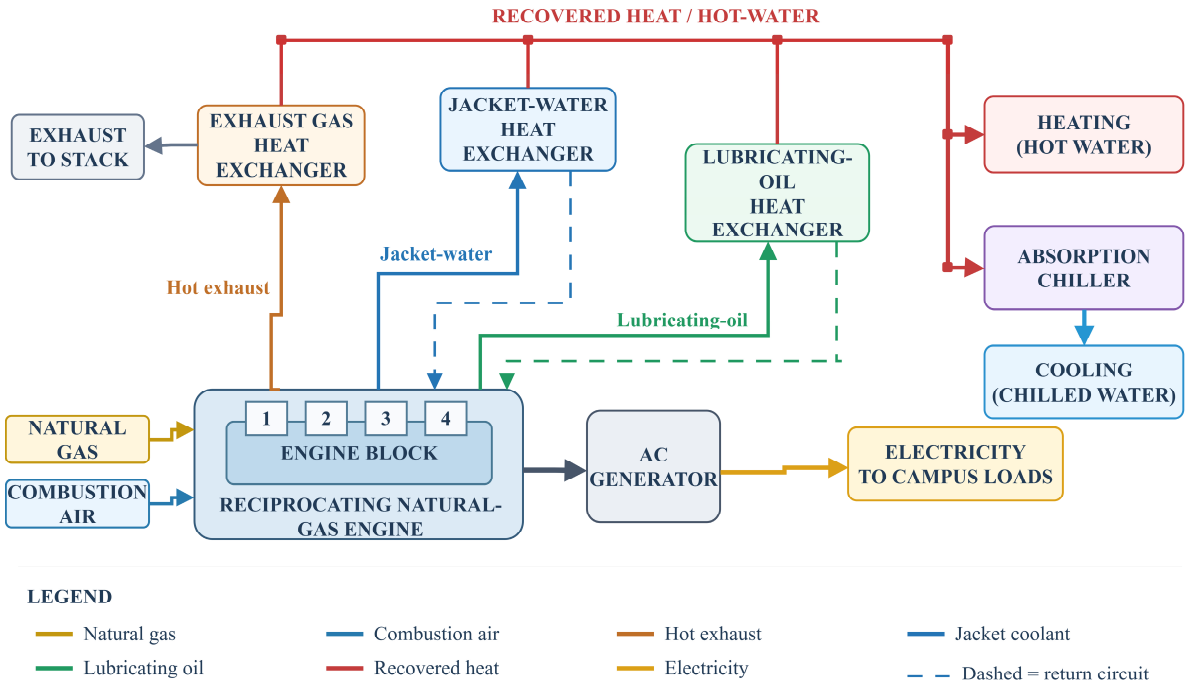


Figure 2. Conceptual schematic of a natural gas-fired reciprocating engine integrated with exhaust gas, jacket water, and lubricating oil heat recovery systems for combined cooling, heating, and power (CCHP) generation. Diagram independently developed by the authors; technical principles supported by [22].

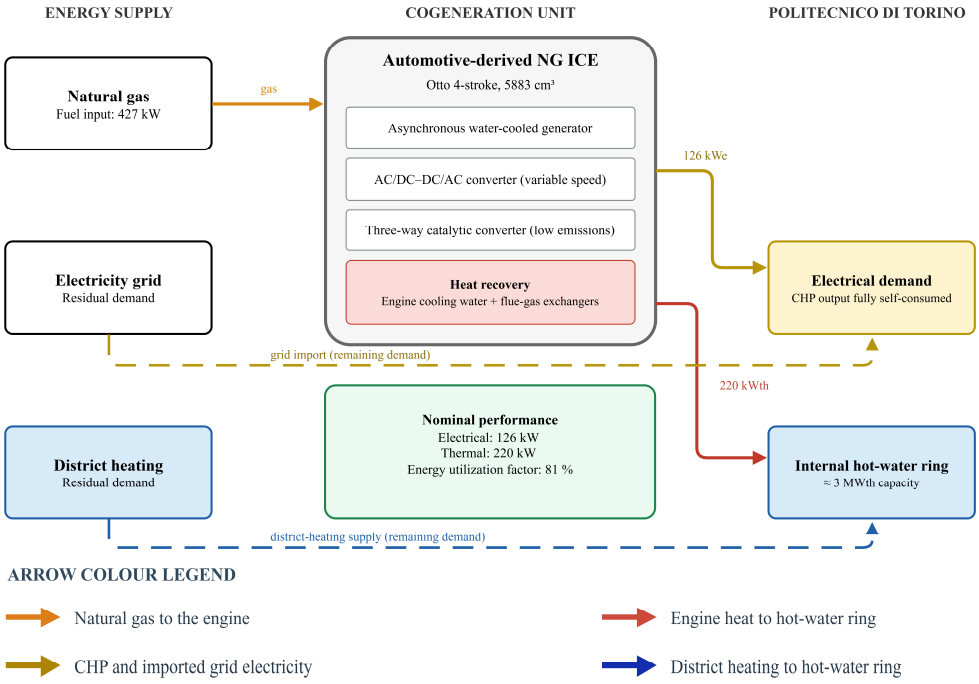


Figure 3. Conceptual schematic of electricity and thermal energy supply at Politecnico di Torino, illustrating the integration of cogeneration with grid electricity, natural gas, and district heating. Independently developed the diagram using technical information reported in [23].

6.2. Gas Turbines

Gas turbines are a versatile, low-maintenance technology for distributed generation, ranging in size from small units to hundreds of megawatts. They are particularly effective

in trigeneration systems because they produce high-quality waste heat from their exhaust gases, which a heat recovery steam generator (HRSG) can capture to produce steam or hot water. Total system efficiency can improve significantly, reaching 65% to 85% Figure 4 [24].

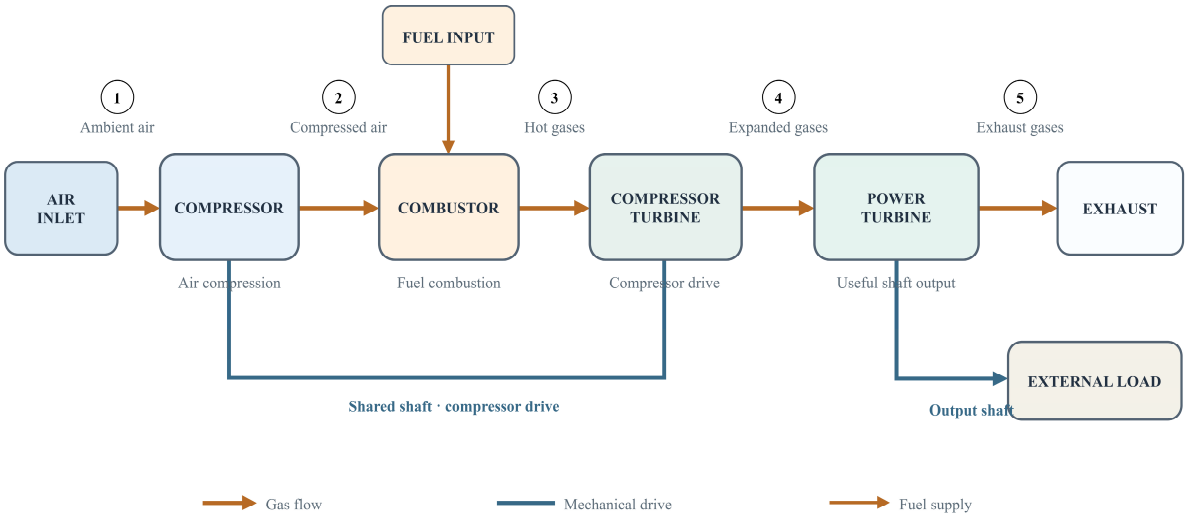


Figure 4. Conceptual schematic of a two-shaft gas turbine system, illustrating the compressor, combustor, compressor-driving turbine, power turbine and external load. The diagram was developed using technical information reported in [24].

At the University of Catanzaro Germaneto Campus, MGE Servizi Energetici has operated a natural gas trigeneration plant since 2010. The system centres on a 4.5 MW gas turbine, paired with a recovery steam generator and an absorption chiller, to maximise efficiency and provide electricity, heating, and cooling for the campus's climate control. The plant produces 23,059 MWh of electricity per year, and it recovers 15,814 MWht of thermal energy per year [25].

6.3. Steam/Combined Cycle

A combined-cycle power plant uses two thermal cycles to generate electricity. One cycle uses the fuel input, and the other uses the rejected heat through a heat recovery mechanism. This configuration works because Brayton-cycle exhaust gas is typically hot enough to provide the heat addition that the Rankine cycle requires. Gas turbine exhaust can exceed 500 degrees Celsius, near the temperature at which modern steam turbines usually operate [26]. Natural gas-fired systems can reach nearly 60% efficiency, with electricity output ranging from 5 to 200 MWe [27].

6.4. Microturbines

Using multiple fuels and biofuels, microturbines are a relatively new electric power generation technology that can often produce heat and power together with high efficiency [28]. They can serve small- and medium-sized commercial and industrial energy applications [29]. Microturbines range from about 20 to 350 kW. For microturbines to succeed, they must be compact, low-cost-to-manufacture, highly efficient, quiet, quick to start, and low-emission [30,31]. Microturbines typically achieve 25% to 35% efficiency, with medium heat recovery Figure 5.

The smart polygeneration microgrid (SPM) at the University of Genova, Savona campus, is a real-world test-bed facility designed to meet the electrical and thermal demands of a university district. The system's generation capacity is provided by a suite of distributed

cogeneration prime movers, primarily micro gas turbines. The campus consists of three microturbines and an internal combustion engine (ICE) [32].

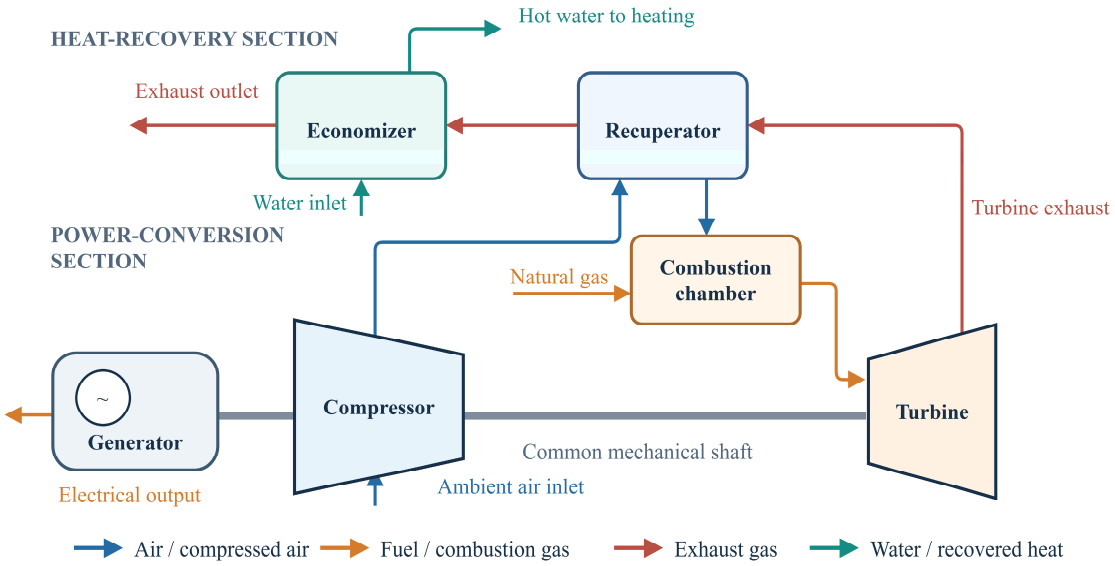


Figure 5. Conceptual schematic of a recuperated gas turbine system incorporating a compressor, combustion chamber, turbine, generator, recuperator and economizer for exhaust-heat recovery. The diagram was developed using technical information reported in [31].

The University of Genova's Savona campus smart polygeneration microgrid (SPM) is a practical test designed to meet a university district's thermal and electrical needs. A collection of distributed cogeneration prime movers, mostly tiny gas turbines—three microturbines and an internal combustion engine (ICE)—make up its generation core [32] (Table 9, Figure 6). About 60% of the campus's electricity needs are met by these units, which are powered by solar panels, two 500 kW auxiliary boilers, and a 12,000 L thermal storage tank. In order to fulfil heat demand, the system operates at full capacity in the winter; in the summer, it is shut down and power is purchased from the grid.

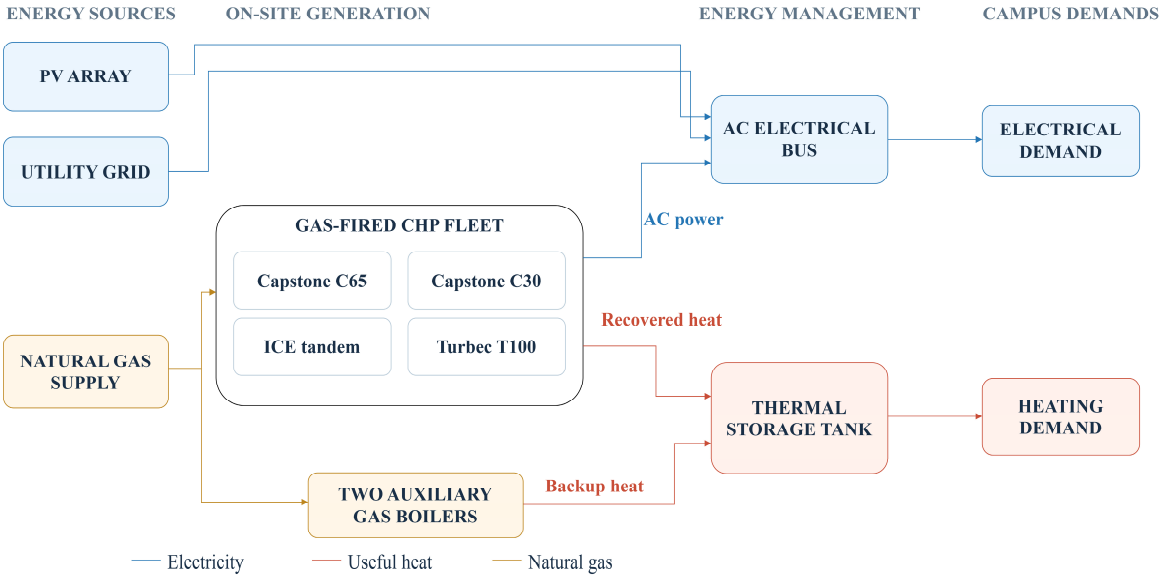


Figure 6. Conceptual schematic of an integrated campus energy-supply system incorporating gas-fired microturbines, an internal combustion engine, photovoltaic generation, grid electricity, auxiliary boilers, and thermal energy storage for meeting electrical and heating demands [32].

Table 9. Specifications of the microturbine and internal combustion engine at the University of Genova.

Prime Movers	Electrical Power [kW]	Thermal Power [kW]
Turbec T100	100	165
Capstone C65	65	112
Capstone C30	30	49
TANDEM T20(ICE)	20	44

Source: Table compiled from the data available in the reference [32].

6.5. Stirling Trigeneration

The Stirling engine is a common name for an external-combustion heat engine that operates on a closed regenerative cycle. Various designs include solar dish/engine installations, biomass systems, air-independent submarine propulsion systems, and on-board power systems for deep-space missions. Researchers have developed Stirling engines for small and micro-CHP applications [33]. A Stirling engine can run on various fuels, including gaseous, solid, and liquid fuels, as well as renewable sources such as solar and geothermal energy. It operates quietly and produces less air pollution [34]. According to (Figures 7 and 8) [35], efficiency ranges from 10% to 80%, depending on the type of Stirling engine and fuel, and electricity generation ranges from 1 kW to 75 kW, with thermal energy output that is medium-to-high. Earlier, the University of Genova, Savona campus had three solar-dish Stirling units generating (3 kWe, 9 kWth), a good example of a Stirling trigeneration project.

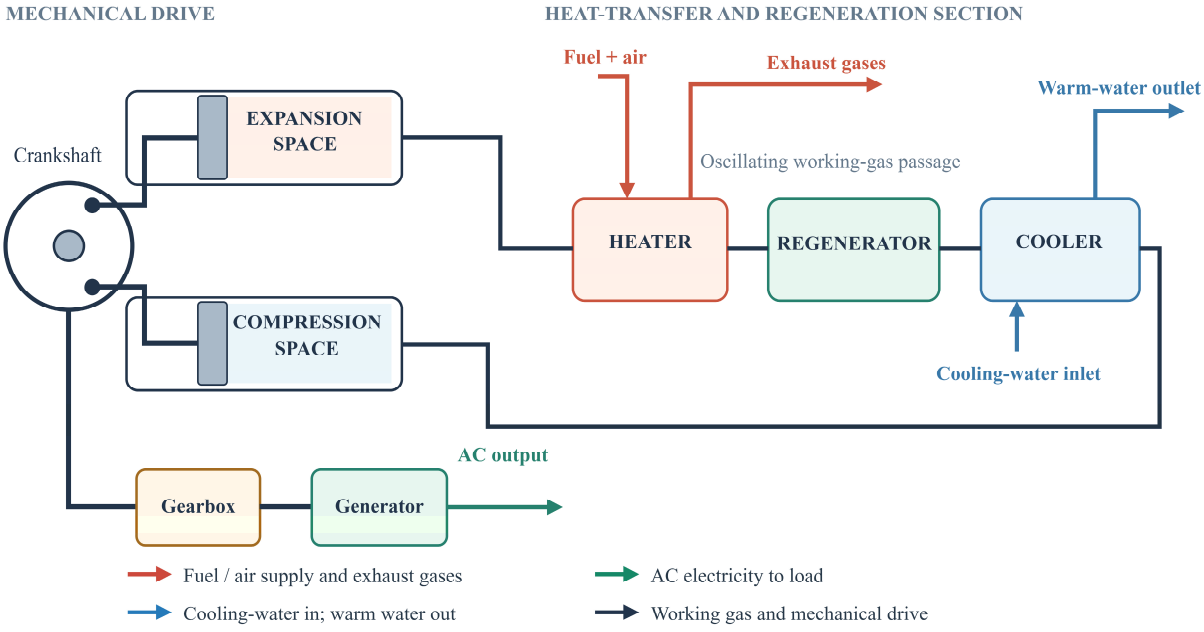


Figure 7. Conceptual schematic of a regenerative Stirling engine system incorporating expansion and compression spaces, a heater, regenerator, cooler, mechanical gearbox and electrical generator. The diagram was developed using technical information reported in [35].

6.6. Organic Rankine Cycle-Based (Heat-Driven) Trigeneration

The organic Rankine cycle (ORC) is a form of energy production used in geothermal, solar, biomass, and water heat recovery applications. It enables the use of various low-temperature heat sources for small- and medium-power generation [36,37]. The ORC is more appropriate for small-scale power generation applications [38]. According to [38], sev-

eral ways classify different versions of ORC; the table below lists them Table 10. Conceptual schematic of an organic Rankine cycle (ORC) system illustrating the evaporator, expander, condenser, feed pump and external heat and cooling-water circuits was illustruated in the Figure 9 using the data from [39].

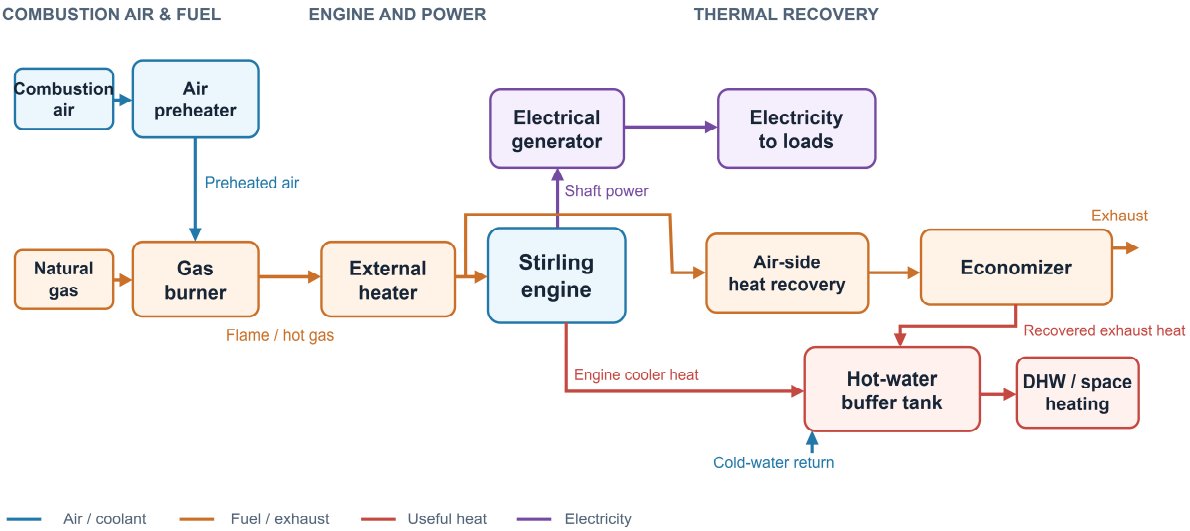


Figure 8. Conceptual schematic of a Stirling engine-based combined heat and power system incorporating combustion, electricity generation, exhaust-heat recovery and hot-water storage. The diagram uses technical principles discussed in [35].

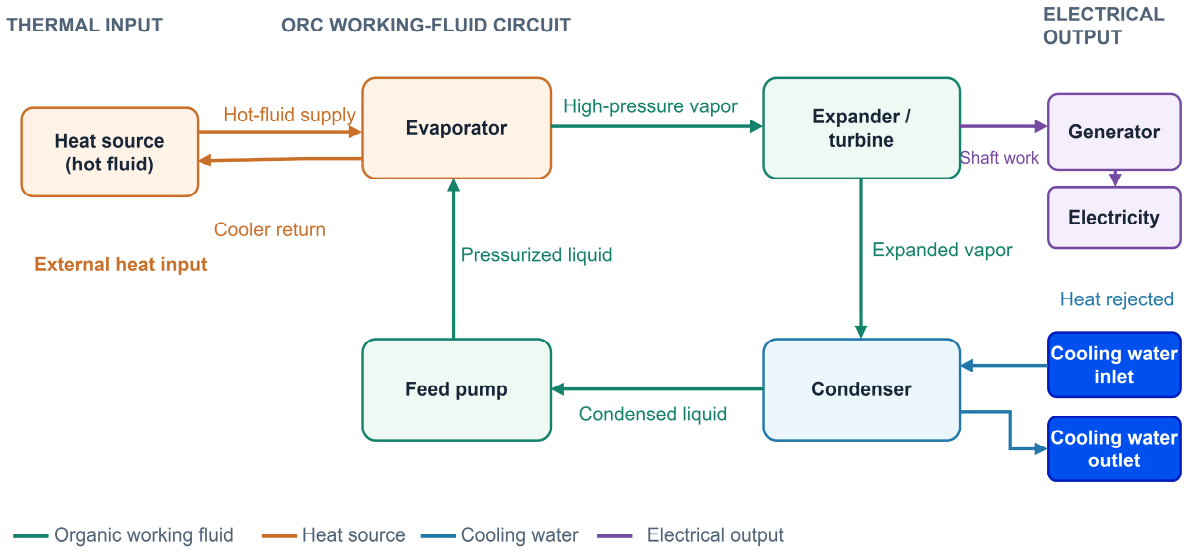


Figure 9. Conceptual schematic of an organic Rankine cycle (ORC) system illustrating the evaporator, expander, condenser, feed pump and external heat and cooling-water circuits. Diagram prepared using technical principles discussed in [39].

Table 10. Classification of organic Rankine cycle systems according to electrical power capacity and required heat source temperatures.

System	Range Electricity [kW]	Required Heat Source Temperature [°C]
Micro Range	0.5–10	50–90
Low	10–100	55–150

Table 10. *Cont.*

System	Range Electricity [kW]	Required Heat Source Temperature [°C]
Medium	100–300	150–300
Large	Above 300	Above 300

Source: Compiled based on the technical characteristics and reported performance values of organic Rankine cycle (ORC) systems presented in the published literature [36–38].

6.7. Fuel Cell Trigeneration

In recent years, fuel cell-based systems have gained significant attention for residential applications (0.5–5 kW) because, compared with conventional power generation technologies, they offer operational advantages, including higher efficiency, reduced noise and vibration, greater fuel flexibility, and lower emissions. Fuel cells are a versatile energy technology with a capacity range from 5 kW to 2 MW, using hydrogen or hydrocarbon-based fuels to generate power. These systems exhibit electrical efficiencies of 37–60%, reaching overall efficiencies of 85–90% (Figure 10, Tables 11 and 12).

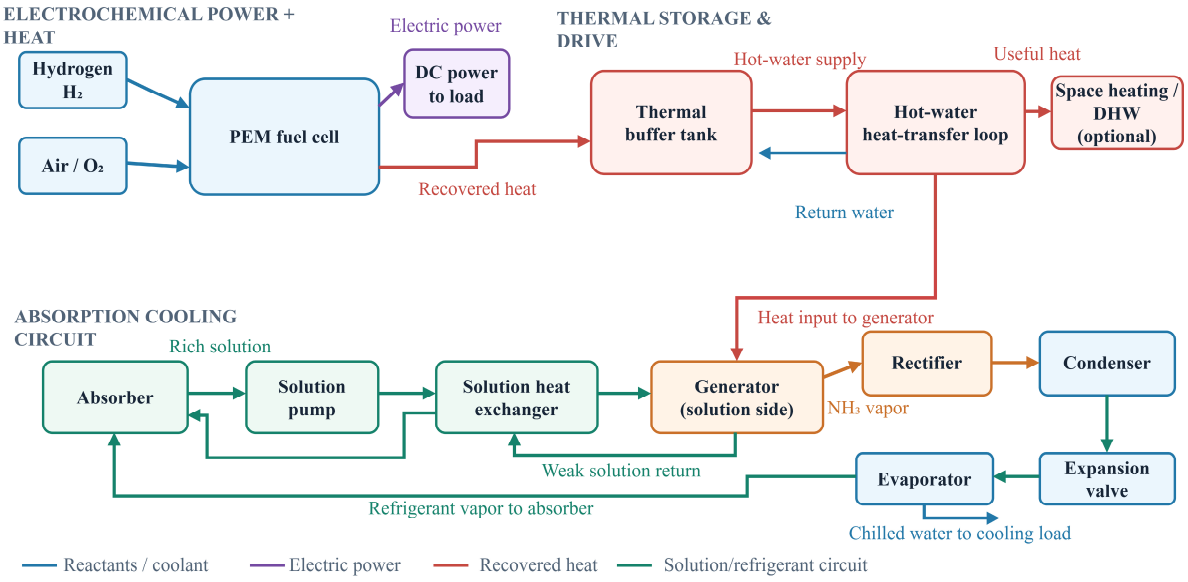


Figure 10. Conceptual schematic of a proton-exchange membrane fuel cell (PEMFC) coupled with thermal energy storage and a heat-driven absorption cooling system. Diagram prepared using technical principles discussed in [40].

Table 11. Comparative technical characteristics, electrical efficiencies, operating temperatures, and waste-heat recovery potential of fuel cell technologies and hydrogen-fuelled engine-generator systems.

	Low/Medium Temperature Fuel Cell Design			High Temperature Fuel Cell Design		Hydrogen Engine Gen-set
TECH.TYPE	PEMFC	AFC	PAFC	MCFC	SOFC	ICE/ Generator
Typical electrical efficiency [%]	30–50	30–50	37–42	50–60	45–60	25–35
Operating temperature [°C]	80	65–250	150–220	650	1000	>1000

Table 11. *Cont.*

	Low/Medium Temperature Fuel Cell Design			High Temperature Fuel Cell Design		Hydrogen Engine Gen-set
Waste heat grade	Low	Low–medium	Medium	High	High	High
Waste heat use (typical)	Hot Water, Abs. Cooling	Hot Water, Abs. Cooling	Hot Water, Steam, Process Heat	Steam, Process Heat, Abs. Cooling	Steam, Process Heat, Abs. Cooling	Steam, Process Heat, Abs. Cooling

Source: Compilation based on technical performance characteristics and waste-heat utilisation data reported in [40].

Table 12. Technical specifications and operational performance characteristics of fuel cell-based combined heat and power systems.

	Fuel Cells
Capacity range [kW]	5–2000
Fuel used	Hydrogen and fuels
Electrical efficiency [%]	37–60
Overall efficiency [%]	85–90
Power-to-heat ratio	0.8–1.1
Output heat temperature [°C]	269–370
Service life [years]	10–20
Noise	Quiet

Source: Compiled based on technical specifications and performance data reported in the published literature [40].

6.8. Solar-Integrated Trigeneration

Among renewable energy technologies, PV is one of the fastest-growing options. A solar photovoltaic (PV) system generates electricity using components such as PV panels, an inverter, a battery, mounting structures, and other balance-of-system components. They play a vital role in generating renewable power. They have a lifespan of roughly 25–30 years [41]. Solar-PV systems offer several advantages, including simple design, long operating life, high reliability, and no additional pollution during energy provision [42]. The main solar-side component was the solar collector field. Scholars and researchers have reviewed numerous collectors available on the market. Comparison of solar collector technologies based on reported efficiency ranges and operating temperature levels were tabulated in Table 13.

For solar-integrated trigeneration to fulfil "tri" generation, the system needs to produce heat, cooling and power. Heat production was carried out by solar collectors, cogeneration units, prime movers, and auxiliary heaters, which satisfy the energy demands. Absorption chillers or auxiliary chillers fulfilled the cooling demand. Power was generated from both prime movers and solar collectors.

Table 13. Comparison of solar collector technologies based on reported efficiency ranges and operating temperature levels.

Solar Collectors	Overall Efficiency [%]	Temperature Level	Reference
Flat Plate Collector (FPC)	20–80	Low-to-Medium	[43]
Evacuated Tube Collector (ETC)	50–75	Medium-to-High	[44]
Compound Parabolic Collector (CPC)	40–70	Low-to-Medium	[45]

Table 13. *Cont.*

Solar Collectors	Overall Efficiency [%]	Temperature Level	Reference
Parabolic Trough Collector (PTC)	40–70	Medium-to- High	[46]
Linear Fresnel Collector (LFC)	37–60	High	[47]
Photovoltaic Panel (PV)	4–46	Not a thermal collector	[48]
Photovoltaic Thermal Collector (PVT)	28.5–85	Low-to-Medium	[49,50]
Concentrating PVT (CPVT)	59.5–85.3	Medium-to-High	[51]

Source: Compiled the table based on reported efficiency ranges and operating temperature levels obtained from previously published studies [43–51].

The University of Palermo hosts a pilot trigeneration plant developed under the EU projects STS-MED. This is also an example of the ORC trigeneration system. This system integrates concentrated solar power (CSP), a biomass boiler, thermal energy storage (TES), and an absorption chiller. The solar field covers about 2000 m^2 and is divided into three parallel linear Fresnel collectors. The collected heat is transferred by an ecological diathermic oil (HTF) working up to 270 °C. The plant has a peak thermal power of 230 kW, and the annual estimated thermal energy production is about 310 MWh. The plant stores the generated thermal energy in a thermal energy storage system (TES). Electrical energy is produced by the ORC engine, and cooling energy is provided by an absorption chiller [52]. University of Palermo conceptual schematic of an integrated solar energy system incorporating a solar collector, heat-transfer fluid circuit, thermal energy storage (TES), power generation block, building heating and cooling system, and water treatment unit. The diagram (Figures 11 and 12) was prepared using technical information from [52].

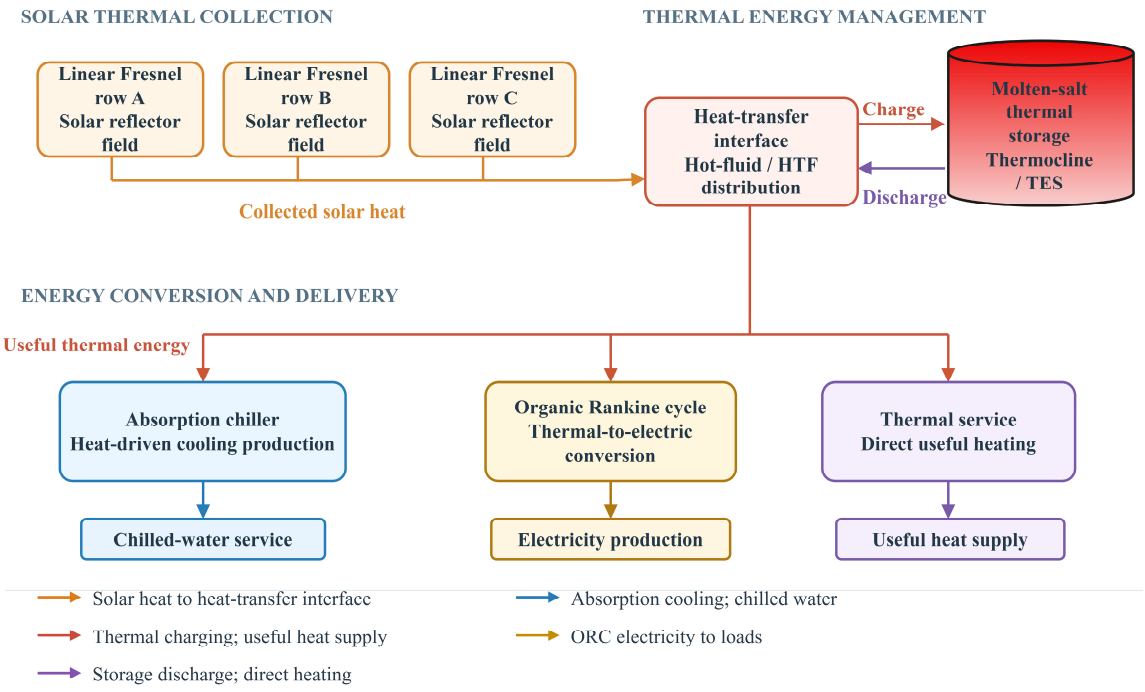


Figure 11. University of Palermo solar-integrated trigeneration system: Conceptual schematic of a solar-assisted trigeneration system integrating Linear Fresnel collectors, molten-salt thermal energy storage, an absorption chiller, and an organic Rankine cycle (ORC) power generation unit. The diagram was prepared using technical information from [52].

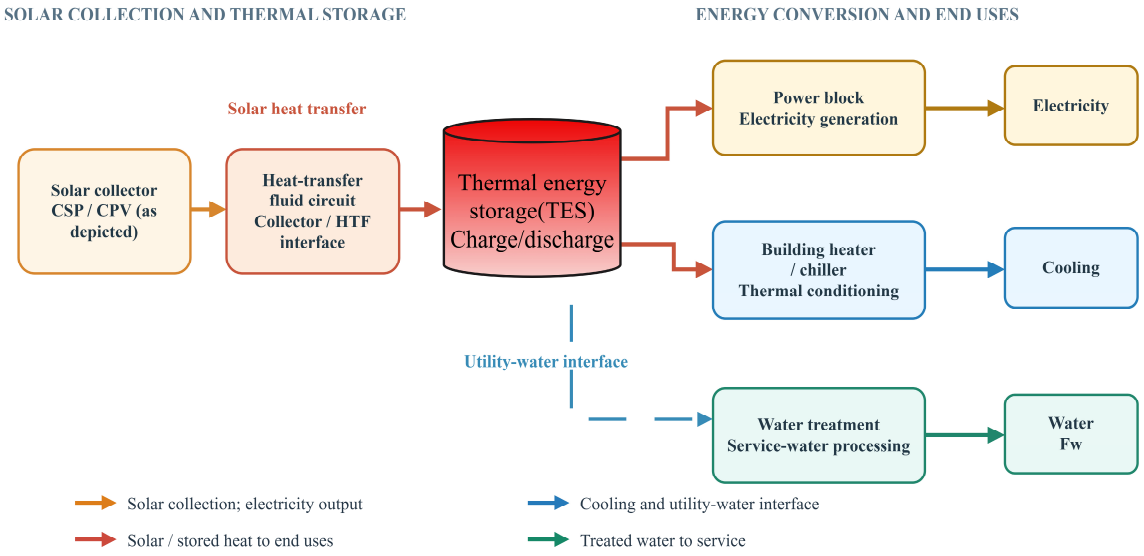


Figure 12. Conceptual schematic of an integrated solar energy system incorporating a solar collector, heat-transfer fluid circuit, thermal energy storage (TES), power generation block, building heating and cooling system, and water treatment unit. The diagram was prepared using technical information from [52]. The schematic is shown for illustration and is not specific to the Palermo plant.

7. Findings and Discussion

7.1. Basis and Scope of the Findings

This section consolidates evidence from Sections 3–6: institutional energy data, degree-day indicators derived from public weather data, and reported characteristics of documented campus installations. The review does not contain measured hourly load profiles, capital or operating cost data, or emission inventories for the campuses studied. The findings are therefore screening-level observations. Each statement below is tied to the evidence that supports it, or is marked as not demonstrated.

Each finding in Sections 7.2–7.5 carries one of three evidence statuses: S supported by the reported data; H a hypothesis consistent with the data but not testable with them; and X not assessable with the available data. The main findings are classified as follows.

Supported by the available data (S):

- Reported 2024 electricity use of five campuses, with their accounting boundaries (Table 3), and a lower-bound harmonised band of 36.6 to 47.2 GWh per year (4.2 to 5.4 MW) for four of them;
- Heating-dominated outdoor temperature exposure in all five cities in 2023 and 2024, with a cooling share of about 30% in Rome and Naples and 10 to 17% in Milan, Turin and Padua (Table 5);
- The existence, technology and rated capacity of documented plants, and Turin's measured 2024 cogeneration output of 12.9 GWh (Section 7.4);
- The reported summer shutdown of the Savona microgrid.

Hypotheses, consistent with but not tested by the data (H):

- Heat and cooling demand coincide with plant operation at the campuses studied;
- Engine-based CHP with absorption cooling suits heating-led cities, and that modular or solar-assisted units suit Rome and Naples (Table 14);
- Turin's lower equivalent full-load hours reflect heat-led or partial operation;
- Absorption cooling creates a useful summer heat sink.

Not assessable with the available data (X): plant sizing, peak and part-load behaviour, load simultaneity, cost, payback and emission effects.

7.2. Campus Energy Demand

Where reported on a 2024 basis, annual electricity ranges from 25.4 GWh (Politecnico di Milano, a partial end-use figure that excludes student housing and climate-control loads) to 47.2 GWh (University of Naples Federico II), equal to average electrical powers of about 2.9 to 5.4 MW (Table 3). After harmonisation to a lower-bound basis (Section 3), four campuses fall between 36.6 GWh (Turin, 4.17 MW) and 47.2 GWh (Naples Federico II, 5.38 MW), with Sapienza (37.5 GWh, 4.27 MW) and Padua (40.9 GWh, 4.66 MW) between them; the estimated total for Politecnico di Milano (40 to 45 GWh, 4.6 to 5.1 MW) lies in the same band. The typical annual load of these campuses is therefore of the order of 4 to 5 MW average electrical power (S for the four campuses with total or lower-bound figures; H for Politecnico di Milano, whose total is an estimate).

The figures are not like-for-like. They combine total institutional consumption (Turin, Naples), grid purchases only (Sapienza, Padua) and a partial end-use metric (Politecnico di Milano). Thermal demand is reported only in fragments (district heating of 16.9 GWh at Turin; natural gas at Sapienza, Padua and Naples, the last at 12.4 GWh), so heat demand cannot be compared across campuses.

Nominal plant capacity can be compared with average campus power as a rough sizing indicator. Turin's 3.9 MWe equals about 0.93 of its average electrical power of 4.17 MW. Politecnico di Milano's 2 MWe equals about 0.39 to 0.44 of the 4.6 to 5.1 MW implied by its estimated need of 40 to 45 GWh per year. Siena's 0.531 MWe equals about 0.54 of an average power of about 0.98 MW (8.64 GWh per year). Peak demand was not available, so this ratio indicates scale only and is not a sizing criterion.

National enrolment rose from about 1.85 million in 2021/22 to more than 2.0 million in 2024/25, but no campus-level series links enrolment to energy use. Per-student indicators (Table 3) range from about 335 to 663 kWh per student for the five campuses, and Padua's grid import equals about 67 kWh/m^2 on the reported 606,566 m^2 estate. However, the estate and the metered boundary may not coincide. Because the boundaries differ and the order of the values does not follow the boundary classes, these values cannot show an enrolment effect. Laboratories, residences, health-care buildings and operating hours probably matter more than headcount, but this review cannot quantify them because of limited available data.

7.3. Climate Exposure and Preliminary Technology Screening

Table 5 shows that the five selected cities experience distinct climatic conditions. In 2024, Turin had the highest HDD (2276.4 °C·days), whereas Rome had the highest CDD (551.4 °C·days). Between 2023 and 2024, CDDs increased at every location, with the largest percentage changes at Padua (+38.6%), Rome (+30.9%) and Naples (+29.6%). Although the CDD/HDD ratio indicates the relative importance of cooling-related outdoor temperature exposure within each city, it does not equal the ratio of measured building cooling to heating loads [16,17]. These year-to-year differences are inter-annual variability over two years and are not evidence of a climate trend (Section 4).

In the heating-led cities (Milan, Turin and Padua, where cooling is below 20% of total degree days), high HDD and the documented campus heat-recovery infrastructure at Politecnico di Milano and Turin make the continued assessment of engine-based CHP with absorption cooling relevant (H). In Rome and Naples, where cooling accounts for about 30% of total degree days, summertime cooling applications merit closer examination, including absorption cooling where a usable heat source exists (H). These are hypotheses for further study. The data do not show that heat and cooling demands coincide with plant operation (X), and the candidates are not a numerical ranking of economic or environmental performance.

Table 14. Climate-informed preliminary screening of trigeneration configurations in selected Italian university locations (2024). HDDs and CDDs are listed separately; the ratio is CDDs divided by HDDs.

Location	HDDs 2024 (°C Days)	CDDs 2024 (°C Days)	CDD/HDD	Ratio	Technical Justification	Candidate Configuration to Examine
North	1951	280	280/1951	0.14	Class H. High heating exposure supports winter heat recovery; summer cooling allows recovered heat to serve an absorption chiller. An operational example already exists. (Section 7.4)	Reciprocating-engine CHP + absorption chiller
West	2276	251	251/2276	0.11	Class H. Highest heating exposure of the five cities. Existing engines and thermal distribution infrastructure support heating-led operation with summer absorption cooling.	Modular ICE-based trigeneration
East	1880	377	377/1880	0.20	Class H. Significant heating exposure, with a 38.6% increase in CDD. Worth examining seasonal switching between heating and cooling.	Flexible reciprocating-engine CHP + absorption cooling
Centre	1190	551	551/1190	0.46	Class M. Highest cooling exposure among the five cities. Modular generation could serve selected building clusters, provided recoverable heat and cooling demand coincide.	Distributed microturbine or small ICE trigeneration
South	1039	443	443/1039	0.43	Class M. Relatively high cooling exposure makes it worth investigating summer cooling integration. Solar generation could complement a thermal CHP system where solar resources and thermal loads are sufficient.	Solar-assisted ICE trigeneration with absorption cooling

Sources: Authors' 2023–2024 Open-Meteo/Eurostat degree-day calculations (Table 5), institutional energy records and case studies discussed in Sections 3–6 [9–19]. HDDs and CDDs are in °C·days. CDD/HDD is a dimensionless ratio of outdoor temperature indicators, not a ratio of building cooling to heating loads. Climate class: H, cooling share below 20% of total degree days; M, 20% or more. Class H defines heating-led; Class M define mixed.

Recommendations are conditional technology candidates, not validated optimal installations. Climatic ratios come from our 2024 Open-Meteo/Eurostat calculations. Assess system performance and suitability at the building or campus level. The table is a qualitative screening heuristic, not a validated decision model; its rules are stated so they can be checked. Rule 1 (climate class): The cooling share of total degree days, CDD/(HDD + CDD), classifies a city as heating-led (class H, below 20%) or mixed (class M, 20% or more). The shares are 12.6% (Milan), 9.9% (Turin), 16.7% (Padua), 31.7% (Rome) and 29.9% (Naples); any cut-off between 17% and 29% gives the same classes, so the split does not depend on the threshold chosen. Rule 2 (infrastructure evidence): A configuration is listed as a candidate only if the same technology family has a documented university installation in a city of the same climate class (Milan and Turin for class H; Sapienza for Rome in class M) or a documented pilot in the same zone (Palermo for Naples). Rule 3 (pairing): lass H cities with documented engine CHP and heat recovery (Milan, Turin) are paired with engine CHP and absorption cooling; Padua, the class H city with the highest cooling share, is paired with flexible engine CHP and absorption cooling; the class M cities are paired with modular units (Rome, where Sapienza operates microturbine and small engine units) or solar-assisted engine trigeneration (Naples). Rule 3 relies on the authors' judgement and is not derived from load data, so that other analysts could pair the same climate class with different technologies. The climate class does not determine technical suitability, which depends on building loads, peak demand and the coincidence of heat and cooling demand (X).

7.4. Technology Screening

Each technology is assessed against four questions: (i) what is its typical unit scale, compared with the average electrical power of the campuses studied (2.9 to 5.4 MW as reported, or about 4 to 5 MW on the harmonised basis), used only as an order-of-magnitude reference because peak demand, load variability and part-load operation are not available; (ii) can its heat be used on a campus, through heating or absorption cooling; (iii) is there a documented university installation, and in which zone; and (iv) what condition limits its use. The three zone columns do not rank technologies by cost or efficiency, and the codes record the strength of evidence; they are not suitability verdicts. The codes are assigned by the following rules, applied in this order. D: At least one documented, operating university installation in that zone, with capacity reported in an institutional or supplier source. P: Otherwise, a pilot or demonstration installation at a university in that zone. N: Otherwise, no university case is documented anywhere, and the smallest typical unit (about 5 MWe for combined cycle) is comparable to or larger than the highest average campus power (5.4 MW), so the technology could serve a campus only through a district network. C: All remaining cases, in which no documented university case exists in that zone, but the scale, heat grade and heat use are plausible from the reported characteristics. N therefore does not mean that a technology is technically unsuitable, and D does not show that an installation operates effectively, because the sources rarely report measured operation.

The absence of a documented installation in a zone is a gap in the evidence and not evidence of unsuitability. The eight rows are not equivalent categories. Rows 1 to 5 and row 7 (internal combustion engine, gas turbine, steam or combined cycle, microturbine, Stirling engine and fuel cell) are prime movers. The organic Rankine cycle (row 6) is a heat-driven power cycle that can be fed by waste heat, solar or biomass heat, and solar-integrated trigeneration (row 8) is a system configuration that can be combined with any of the prime movers and is not an alternative to them. They are listed together because the literature on university applications presents them as options; the first column of Table 15 states the category of each row, and the codes for row 8 refer to integrating solar collectors or PV with a CHP block.

Table 15. Evidence-based screening of trigeneration technologies for university campuses.

Technology	Typical Scale [MWe]	Scale Matches Campus Load (Indicative Only)	Heat and Cooling Coupling	Documented University Evidence in This Review	North	Centre	South	Main Condition or Limitation
Internal combustion engine (ICE) (Prime mover)	0.1 to 10	Good. Brackets the 2.9 to 5.4 MW average campus power. Installed units are about 0.4 to 0.9 of average demand.	Jacket and exhaust heat; hot water or district heating; LiBr–water absorption chiller (about 1.4 MWc at Politecnico di Milano); desiccant option (Politecnico di Torino).	Politecnico di Milano 2 MWe; Turin 3 × 1.3 MWe (generation measured, 2024); Sapienza 580 and 250 kWe CHP units; Politecnico di Torino 126 kWe demonstration.	D	D	C	Needs a steady heat base. No southern university case documented.
Gas turbine (Prime mover)	1 to 50	Marginal. Only the lower end fits; units above about 5 MWe exceed average campus power unless they serve a district network.	High-grade exhaust; heat recovery steam generator; single- or double-effect or steam-driven absorption.	Catanzaro Germaneto: 4.5 MW, in operation since 2010; 23,059 MWh/y electricity and 15,814 MWh/y heat (supplier-reported).	C	C	D	Large, continuous heat demand. One case from a company website.
Steam or combined cycle (Prime mover)	5 to 200	Poor. Exceeds the average power of every documented campus (maximum 5.4 MW).	Steam-driven absorption, via district heat networks.	None documented.	N	N	N	Conceivable only within a city-scale network, outside single-campus scope.
Microturbine (Prime mover)	0.02 to 0.35	Modular. Suits buildings, clinical units or small campuses; many units are needed to approach 1 MWe.	Exhaust heat; heat-to-power ratio about 1.6 to 1.7 in documented units; absorption or adsorption chillers.	Sapienza 100 kWe/ 167 kWth with absorption; Genova Savona 100 + 65 + 30 kWe, reported to cover about 60% of campus electricity.	D	D	C	Electrical efficiency 25 to 35%. Savona is switched off in summer, so the thermal sink limits operation.
Stirling engine (Prime mover)	0.001 to 0.075	Too small. At most 75 kWe, under 3% of average campus power.	External combustion; medium-to-high heat output; absorption.	Earlier 3 x (3 kWe/ 9 kWth) solar dish Stirling units at Genova Savona (demonstration).	P	C	C	Research or demonstration value; not a campus supply option.

Table 15. *Cont.*

Technology	Typical Scale [MWe]	Scale Matches Campus Load (Indicative Only)	Heat and Cooling Coupling	Documented University Evidence in This Review	North	Centre	South	Main Condition or Limitation
Organic Rankine cycle (ORC) (heat-driven power cycle)	0.0005 to >0.3 (classes in Table 10)	Low-to-moderate. Output depends on the heat source, not on campus load.	Heat source 50 to 300 °C (solar thermal, biomass, waste heat); absorption, adsorption or ejector cooling.	Palermo STS-MED pilot: solar Fresnel field, biomass boiler, storage, ORC and absorption chiller; 230 kWth peak, about 310 MWh/y heat (estimated).	C	C	P	Needs a low-grade heat source; low electrical efficiency.
Fuel cell (Prime mover)	0.005 to 2	Modular; scale-up limited by capital cost and 10 to 20 year life (not quantified in the sources).	Electrical efficiency 37 to 60%; power-to-heat ratio 0.8 to 1.1; absorption cooling.	No Italian university installation documented in the sources reviewed.	C	C	C	Fuel supply (hydrogen or reformed gas) and cost not examined in the sources.
Solar-integrated (CHP + solar thermal or PV) (system configuration)	0.1 to 10 (CHP block)	Depends on collector area and the CHP block; solar covers only part of the heat.	Collectors (Table 13), CHP, auxiliary boiler, storage; absorption chiller.	Palermo pilot (as above); Genova Savona microgrid with PV and a 12,000 L thermal store.	P	C	P	Solar supply peaks in summer, when heating demand is lowest; it aligns with cooling, not with winter heating in the north.

Three results follow. First, reciprocating engines are the best-documented option at multi-megawatt campus scale (2 MWe at Politecnico di Milano, 3.9 MWe at Turin), and microturbines are documented at building or small-campus scale (Sapienza, Savona). Second, the gas turbine has one documented university case in southern Italy (Catanzaro, 4.5 MW, about 5100 equivalent full-load hours), and its source is a company web page; in other zones, its scale is large relative to average campus power unless it serves a district network. Combined-cycle plants exceed single-campus scale. Third, Stirling, ORC, fuel cell and solar-integrated options are represented only by pilots or by no case at all and should be treated as research and demonstration options. The evidence does not show that any technology is optimal for a given region. Tables 15 and 16 follow on the next pages.

Zones follow the locations in Sections 3–6. Codes are applied by the rules in Section

D	documented operating university installation in that zone;
P	pilot or demonstration in that zone;
C	conditional (plausible from reported characteristics, no documented university case in that zone);
N	no documented university case and typical unit size comparable to or larger than the highest average campus power (not a verdict of technical unsuitability)

Campus load = 2.9 to 5.4 MW average electrical power, 25 to 47 GWh/y as reported (Table 3), used as an order-of-magnitude reference only. Ratings describe the evidence, not economic or environmental optimality: no cost or emission data were available. MWe, MWth and MWc denote electrical, thermal and cooling capacity—sources: Sections 3–6 and the references cited there.

7.5. Operational Evidence from Documented Plants

Table 16 consolidates the documented plants in one format and separates measured, estimated and forecast values. Three observations follow. First, where on-site generation is documented, it covers roughly a quarter to a third of campus electricity: 35.2% at Turin (reported, 2024), about 27 to 30% at Politecnico di Milano (historical output against an estimated need, so mixed years) and 34.7% forecast at Siena. The 60% reported for Genova Savona refers to a small microgrid campus, and its basis is not stated. Second, utilisation differs. Politecnico di Milano reaches about 6000 equivalent full-load hours per year, Catanzaro about 5100, and Siena is forecast at about 5650. In contrast, the Turin fleet, with a nominal capacity of about 0.93 of average demand, has 3304 equivalent full-load hours (EFLH = annual electricity generated ÷ rated electrical capacity; it is not measured runtime and not efficiency) (a 37.6% capacity factor). The sources do not explain the Turin figure. A heat-led or partial operation is a plausible reading, but it is a hypothesis. The Siena forecast exceeds the only measured multi-unit figure, so we need operating data from its first full year before relying on the forecast.

Table 16. Documented operating indicators of cogeneration and trigeneration plants at university sites.

University (Zone)	Installed Capacity	Reported or Forecast Output	Basis of the Figure	Share of Reported Campus Electricity	Equivalent Full-Load Hours	Heat and Cooling Information	Evidence Quality and Caveat
Politecnico di Milano (North)	2 MWe engine; about 1.4 MWc absorption	About 12 GWh/y electricity (about 11 used on site, 1 exported)	Approximate; BEA 2020 (historical)	About 27 to 30% of the 40 to 45 GWh/y estimated need	About 6000 h (derived)	Absorption figure is rated capacity, not annual cooling	Mixed years; denominator is an estimate
University of Turin (West)	3 × 1.3 MWe = 3.9 MWe	12.887 GWh from CHP in 2024	Reported, 2024	35.2% of 36.64 GWh	3304 h; capacity factor 37.6%	Recovered heat 2400.5 MWh (Palazzo Nuovo) and 2510.8 MWh (Grugliasco); district heating 16.9 GWh reported separately	Generation fraction, not measured self-consumption
Sapienza (Centre)	100 kWe microturbine (trigeneration); 580 kWe Ortopedia and 250 kWe Regina Elena CHP	Not reported for 2024	Installation descriptions	Not determinable	Not determinable	167 kWth (microturbine); 670 kWth (Ortopedia); Regina Elena not recorded	Capacity only; no output to compare
University of Siena (Centre)	531 kWe, installed December 2025	Forecast: 3 GWh electricity, 1.8 GWh heat, 1.4 GWh cooling	Forecast	(34.7% of 8.64 GWh)	About 5650 h (implied)	Heat/electricity 0.60; cooling/electricity 0.47	Forecast
University of Genova, Savona (North)	215 kWe (3 microturbines + 20 kWe ICE); 370 kWth; two 500 kW boilers; 12,000 L store	About 60% of campus electricity demand	Reported; year not stated	About 60%	Not reported	System off in summer; electricity bought from the grid	Single microgrid; basis of 60% not stated
University of Catanzaro (South)	4.5 MW gas turbine, steam generator, absorption chiller	23,059 MWh/y electricity; 15,814 MWh/y heat	Supplier-reported; year not stated	Campus demand not reported	About 5100 h (derived)	Heat/electricity 0.69	Company web page, not peer-reviewed
University of Palermo (South)	Solar field, biomass boiler, storage, ORC, absorption chiller; 230 kWth peak	About 310 MWh/y heat	Estimated	Not applicable	Not applicable	Cooling by absorption chiller	Pilot

Computed values: equivalent full-load hours = annual generation/installed electrical capacity; share = on-site generation/reported campus electricity; Turin capacity factor = 3304 h/8784 h. Measured, estimated, forecast and supplier-reported figures are not combined—sources: Sections 3, 5 and 6 and the references cited there. Inputs and reference periods for each calculation are given in Section 7.5.

Third, the Savona microgrid shows how the thermal and electrical loads interact. It operates fully in winter and switches off in summer, when it buys electricity from the grid instead (Section 6.4). The operating case therefore rests on the availability of a thermal sink: when recovered heat cannot be used, running the prime mover only for electricity was not preferred. The same logic applies to campuses where summer cooling is a larger share of exposure, such as Rome and Naples. Absorption cooling can create a summer heat sink, and its adoption is visible in the roughly 1.4 MWc installed at Politecnico di Milano and the 1.4 GWh/y of cooling forecast at Siena (0.47 of its forecast electricity). No measured summer operating data are available, so these sources cannot determine whether the extra capital cost and lower electrical output of absorption cooling are justified. For cooling-dominated sites, the trade-off between electrical output and usable heat is a central design question. Sizing to the base thermal load, thermal storage and part-load strategies should be evaluated, and this review cannot identify the optimum. Equivalent full-load hours are calculated as annual electricity generated divided by rated electrical capacity: 12,887.195 MWh/3.9 MW = 3304 h for Turin (2024; capacity factor 3304/8784 = 37.6%); about 2000 MWh/2 MW = 6000 h for Politecnico di Milano (BEA 2020); 23,059 MWh/4.5 MW = 5124 h, rounded to about 5100 h, for Catanzaro (supplier-reported, year not stated); and 3000 MWh/0.531 MW = 5650 h for Siena (forecast, implied). EFLH cannot be calculated for plants without generation data (Sapienza, Politecnico di Torino, Savona, and the electricity of the Palermo pilot). The lack of generation data for these plants also prevents any assessment of their contribution to meeting campus demand.

7.6. What Is Specific to University Campuses

Existing trigeneration evaluations [20,21] categorise prime movers, cooling technologies, and operating methods for buildings and industries in general, whereas campus energy assessments [1,2] focus on demand modelling and management. To our knowledge, no assessment has examined published energy statistics for Italian universities, the climatic exposure of their cities, and recorded cogeneration and trigeneration installations on a common basis. This review contributes: (i) a 2024 comparison of institutional electricity data with explicit accounting boundaries (Table 3); (ii) heating and cooling degree days calculated in the same way for five university cities (Table 5); (iii) a consolidated table of documented plants that separates measured, estimated, forecast and supplier-reported values (Table 16); (iv) an evidence-graded screening of eight technologies (Table 15); and (v) the features that are specific to university campuses (Section 7.6) and the data needed for economic and environmental assessment.

Prime-mover efficiencies, scale ranges, and heat grades (Section 6) are technology properties and apply to any building or campus; they are not university-specific findings. The evidence reviewed points to five university-specific features.

Academic calendar: Occupancy falls during summer break, when cooling exposure is highest, and heating demand is lowest. The Savona shutdown corresponds to this mismatch, although the source does not explain it in these terms.

Mixed building stock: Teaching, laboratory, residential and, at some universities, health-care buildings share a portfolio (Section 3). Buildings with continuous occupancy provide a heat base that lecture halls do not. The building-level units at Sapienza are an example of units placed with a specific building rather than with the whole campus.

Multi-site estates: Turin recovers heat separately at Palazzo Nuovo and Grugliasco, and Sapienza has units at different sites. The documented pattern is distributed units (engines, microturbines) and not a single central plant.

Research and teaching mission: Four of the eight documented sites (Genova Savona, Palermo, Politecnico di Torino and the Sapienza microturbine) are described as research,

pilot or demonstration installations of 0.35 MW or less. The evidence for small technologies therefore reflects the universities' research function, not cost-driven deployment.

Institutional reporting: The universities report energy in sustainability and annual reports, but with different boundaries. This limits comparison more than the technologies do, and harmonising Tables 3 and 16 is a contribution of this review.

7.7. Economic, Environmental and Institutional Conditions

The sources reviewed do not report capital cost, operating cost, unit generation cost, payback, net present value, internal rate of return or emission inventories for the campus cases. This review therefore does not claim that trigeneration is cost-effective or lowers emissions at any campus. Both outcomes are conditional.

Economic viability depends on annual equivalent full-load hours (3300 to 6000 equivalent full-load hours in Table 16), how much recovered heat and cooling displaces separate production, fuel and electricity prices, maintenance, and capital cost. Emission reductions depend on electrical and overall efficiency, how much recovered heat is used, and the emission intensity of the grid electricity and boiler heat it displaces. Gas-fired generation can increase emissions if it wastes heat, which the Savona shutdown avoids.

The cases suggest these barriers vary by project scale. The multi-megawatt installations (Milan, Turin, Catanzaro) need capital and procurement arrangements that the institution or a service provider can supply; the Catanzaro plant is described as established by MGE Servizi Energetici, but the contract terms are not documented. The sub-megawatt units appear within research projects (the EU project STS-MED at Palermo) or an energy renovation programme (Siena). These interpretations are based on a small number of cases and do not test differences across campus sizes and regions. Ownership models, energy service contracts and national incentive schemes need contract-level data and are left for future work. A combined thermodynamic, economic, and environmental evaluation, as applied to polygeneration systems [53], would be needed to test these conditions for individual campuses.

7.8. Limitations

- Institutional data are self-reported and use different boundaries; only five universities have 2024 energy data.
- Eight university sites with cogeneration or trigeneration are documented, and their figures mix measured, estimated, forecast and supplier-reported values.
- No monthly or hourly electricity, heat, and cooling profiles were available, so we could not analyse load simultaneity and heat utilisation.
- No capital cost, operating cost, payback, or emission data were available, so no economic or environmental conclusions can be drawn.
- Degree days cover two years and describe outdoor temperature only, and the technology codes and Table 15 are qualitative screening rules and not validated criteria; no conclusion about the suitability of an individual campus can be drawn from them.

8. Conclusions

This research sought to determine whether claims regarding trigeneration's appropriateness for Italian university campuses are backed by published data or are merely conjectural. It used 2024 institutional data for five universities, degree-day indicators for their cities in 2023 and 2024, and the cogeneration and trigeneration plants documented at eight university sites. The conclusions are limited to what this evidence supports.

- Demand: Reported 2024 electricity use ranges from 25 to 47 GWh (average power 2.9 to 5.4 MW), but the figures use different boundaries and cannot be ranked. After

harmonisation to a lower-bound basis, four campuses fall between 36.6 and 47.2 GWh (4.2 to 5.4 MW). Heat demand is mostly unreported.

- Climate: All five cities were heating-dominated in 2023 and 2024. Cooling exposure is proportionally larger in Rome and Naples (about 30% of the combined degree-day total, versus 10 to 17% in Milan, Turin, and Padua) and was 30 to 39% higher in 2024 than in 2023 in Rome, Naples and Padua (two-year variability, not a trend).
- Documented plants: On-site generation covers roughly a quarter to a third of campus electricity: 35.2% at Turin in 2024, about 27 to 30% at Politecnico di Milano and 34.7% forecast at Siena. Equivalent full-load hours range from about 3300 at Turin to about 6000 at Politecnico di Milano.
- Technologies: Reciprocating engines are the best-documented option at multi-megawatt campus scale, and microturbines are documented at the building or small-campus scale. A gas turbine is documented once, in southern Italy. Combined-cycle plants exceed campus scale. Stirling, ORC, fuel cell, and solar-integrated systems are documented only as pilots, or not at all, and should be treated as research options. The evidence does not identify an optimal technology for any region.
- University-specific factors: The academic calendar, mixed building stock, multi-site estates, and research mission shape how trigeneration operates. The Savona microgrid, switched off in summer, shows that a thermal sink, not electrical demand, governs operation.
- Costs and emissions: The reviewed sources contain no capital cost, operating cost, payback or emission data for the campus cases, so this review does not conclude that trigeneration lowers costs or emissions at any campus. These outcomes depend on utilisation hours, use of recovered heat, energy prices and the emission intensity of the displaced grid electricity and heat.
- Evidence status: reported demand, climate exposure and the existence of documented plants are supported by the data (S). The suitability of engine CHP with absorption cooling in heating-led cities, of modular or solar-assisted units in Rome and Naples, and the benefits of absorption cooling are hypotheses (H). Sizing, load coincidence, cost and emissions cannot be assessed (X).

Future work needs to obtain (a) monthly or hourly electricity, heat and cooling data for typical campuses; (b) measured operating data for the plants in Table 16, especially Siena after its first full year; (c) a main energy saving and emission calculation against a separate-production reference; (d) a sensitivity analysis on fuel price, electricity tariff and operating hours; and (e) an analysis of ownership and funding models. Trigeneration is therefore a candidate option to be assessed campus by campus, and no single model suits all campuses. Future assessments could adopt studies of polygeneration systems to show how thermodynamic, economic, and environmental indicators can be combined in a multi-aspect framework [53], and apply such a framework to the Italian campus to enable evidence-based screening with quantitative indicators.

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Conflicts of Interest: The authors declare no conflicts of interest.

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