Multi-Objective Optimization of an Energy Community Powered by a Distributed Polygeneration System

Supplementary Material

Ronelly José De Souza[1,2,*], Mauro Reini[1], Luis M. Serra[2], Miguel A. Lozano[2], Emanuele Nadalon[1], Melchiorre Casisi[1]

[1] Department of Engineering and Architecture, University of Trieste, Trieste, Italy
[2] GITSE-I3A, Department of Mechanical Engineering, Universidad de Zaragoza, Zaragoza, Spain
**Corresponding author: ronellyjose.desouza@phd.units.it*

Contents

1. Energy demands 2
2. Technical data 16
2.1 Internal combustion engine (ICE) 16
2.2 Micro gas turbine (MGT) 18
2.3 Absorption chiller (ABS) 19
2.4 Heat pump (HP) 23
2.5 Solar technologies 25
2.6 DHCN pipelines 28
3. Economic data 29
3.1 Fixed costs plus maintenance factors 29
3.2 Variable costs 31
3.3 Energy resources economic data 31
4. Mathematical model 33
4.1 Objective function: complementary equations 33
4.2 Models of the adopted technologies 36
4.2.1 Buildings 37

4.2.2 Central unit.....41
5. Results (complement) 43
5.1 Optimal economic solution: illustration of the polygeneration systems for each building 43
References.....47

1. Energy demands

The energy demands of the buildings were obtained through three types of procedures: from the literature, from pieces of information found on webpages related to the respective building, and from the owner/manager of the building.

The energy demand data related to buildings 1 to 6 were retrieved from [1]. For what concerns building 7 (hospital), the energy demand data were estimated based on the energy demand of the hospital in the work of [2], who developed a study about a DHN in the city of Tolmezzo, within the same Italian region as Pordenone. A scale factor was calculated based on the number of beds of both hospitals (information obtained through contact with the administration of both hospitals) and, in this way, the energy demand profiles for the hospital of Pordenone was obtained.

In a similar way, the data related to building 8 (secondary school) was estimated based on the number of students (information found on the website of the school) and the energy demands of a similar school, also analyzed in the work of [2].

The energy demand information about building 9 (swimming pool) was obtained through direct contact with the owner of the building, who kindly provided the requested information.

Figure S1 to Figure S9 present the hourly electricity demand during an entire year for each building and for two typical days per month. Figure S10 to Figure S18 and Figure S19 to Figure S27 present similar data, but for heating and cooling demands, respectively.

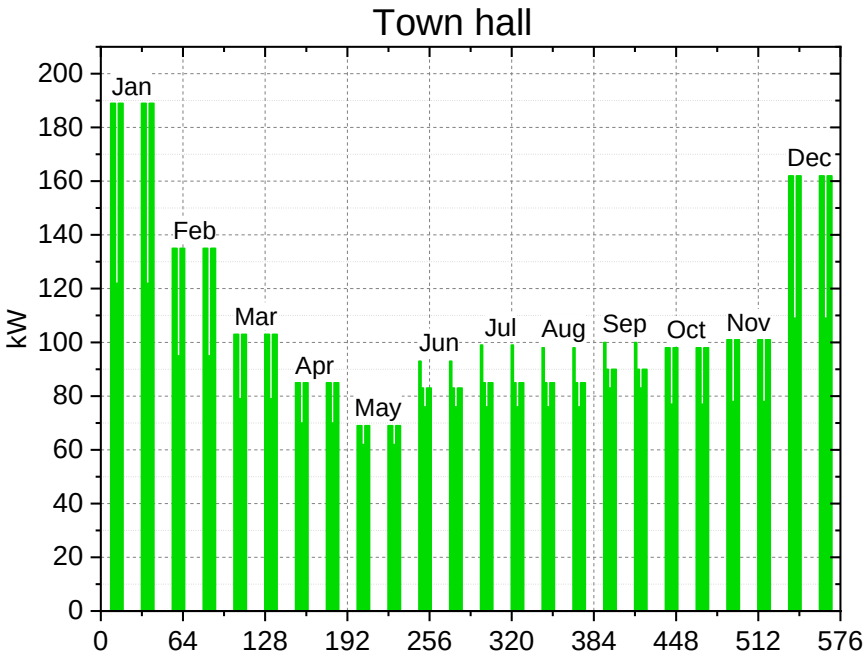


Figure S1. Annual electricity demand profiles (two 24-hours typical days per month) for the Town hall.

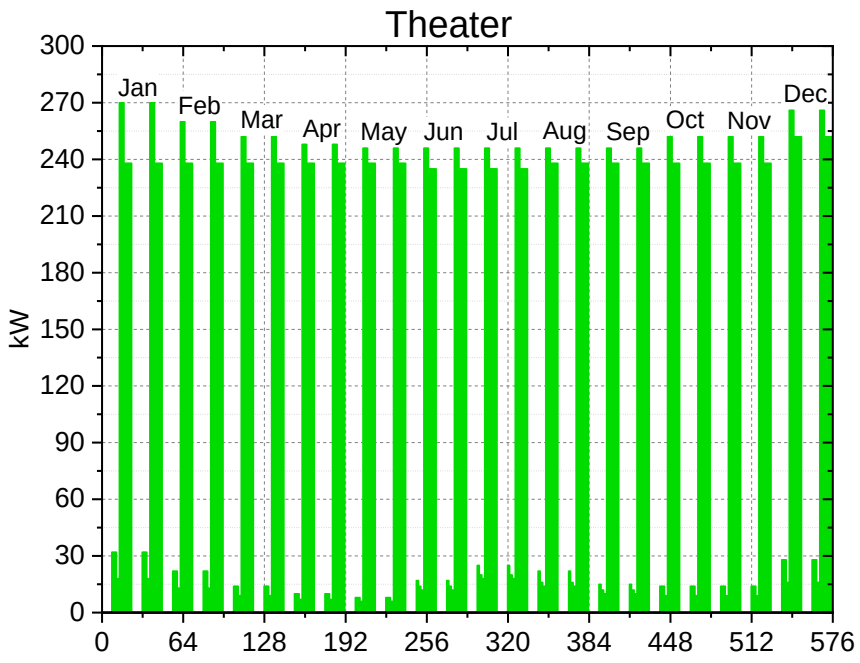


Figure S2. Annual electricity demand profiles (two 24-hours typical days per month) for the Theater.

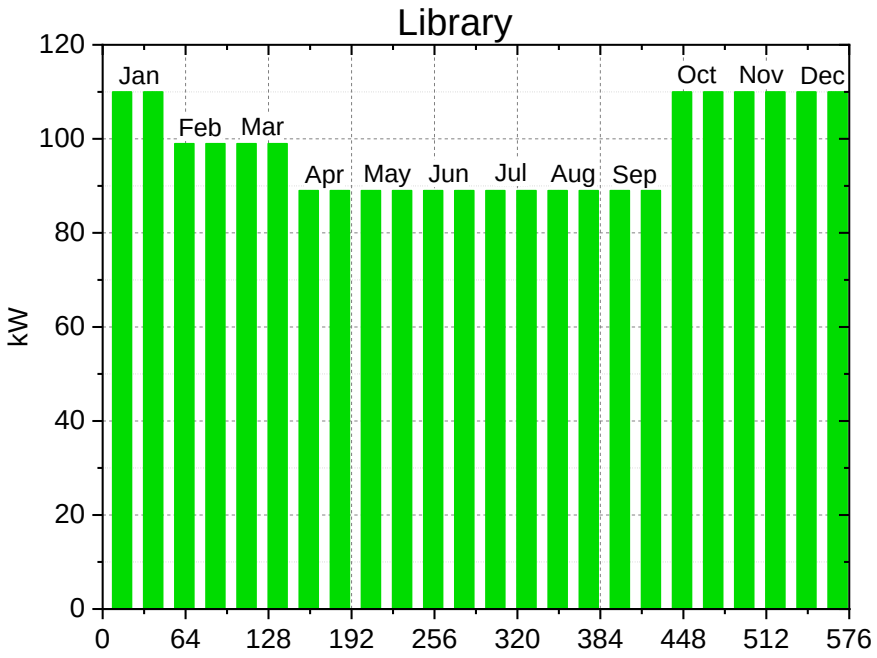


Figure S3. Annual electricity demand profiles (two 24-hours typical days per month) for the Library.

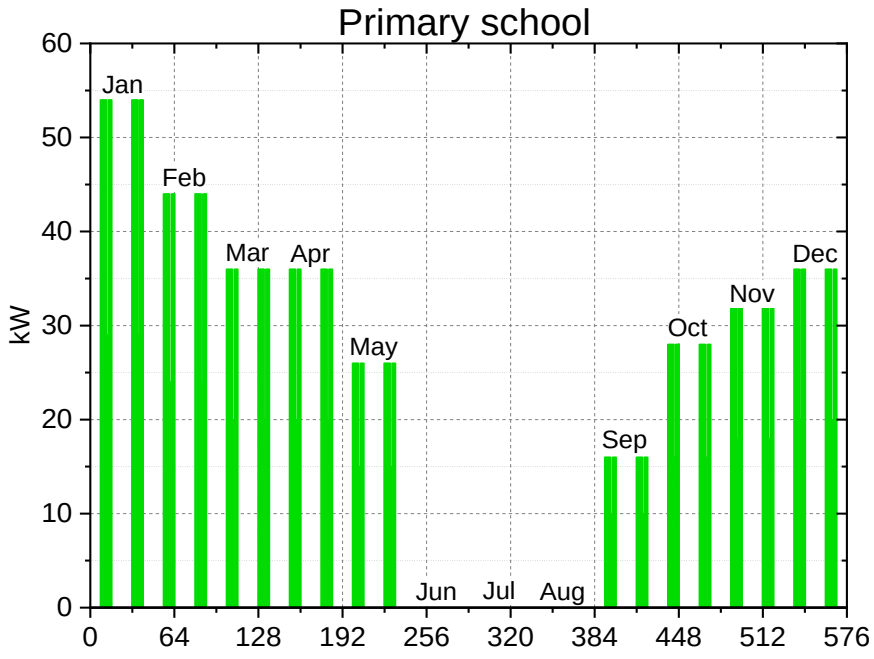


Figure S4. Annual electricity demand profiles (two 24-hours typical days per month) for the Primary school.

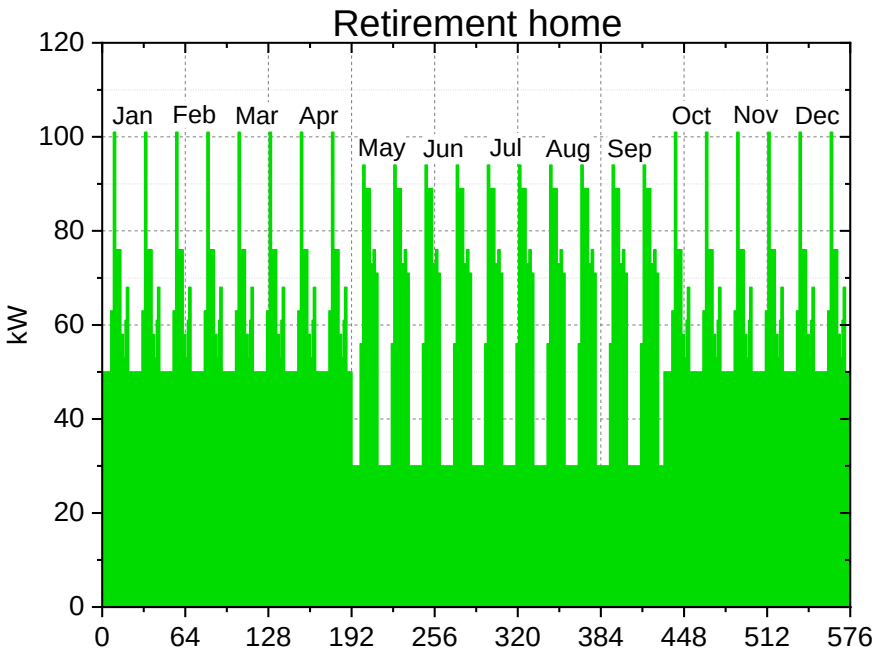


Figure S5. Annual electricity demand profiles (two 24-hours typical days per month) for the Retirement home.

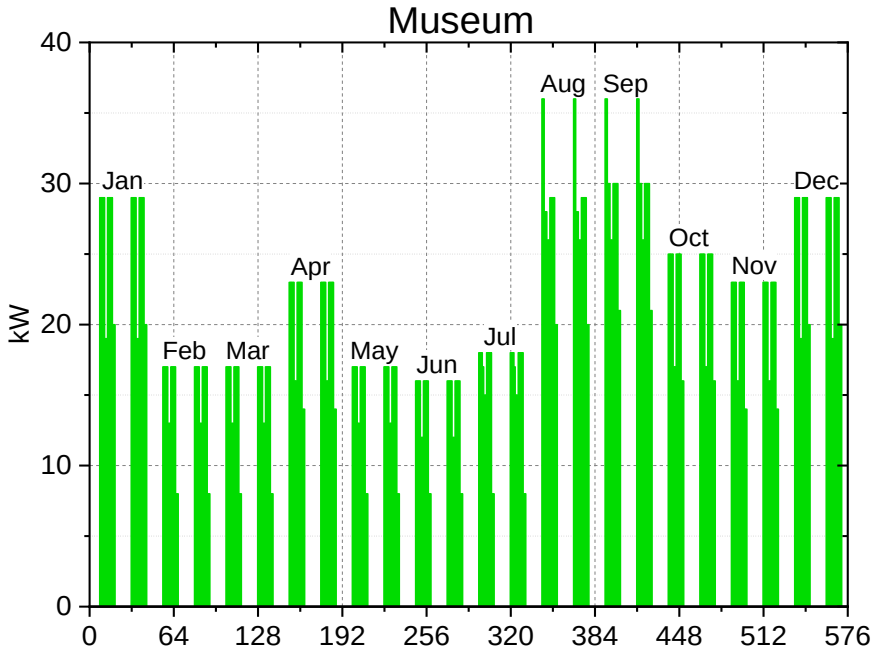


Figure S6. Annual electricity demand profiles (two 24-hours typical days per month) for the Museum.

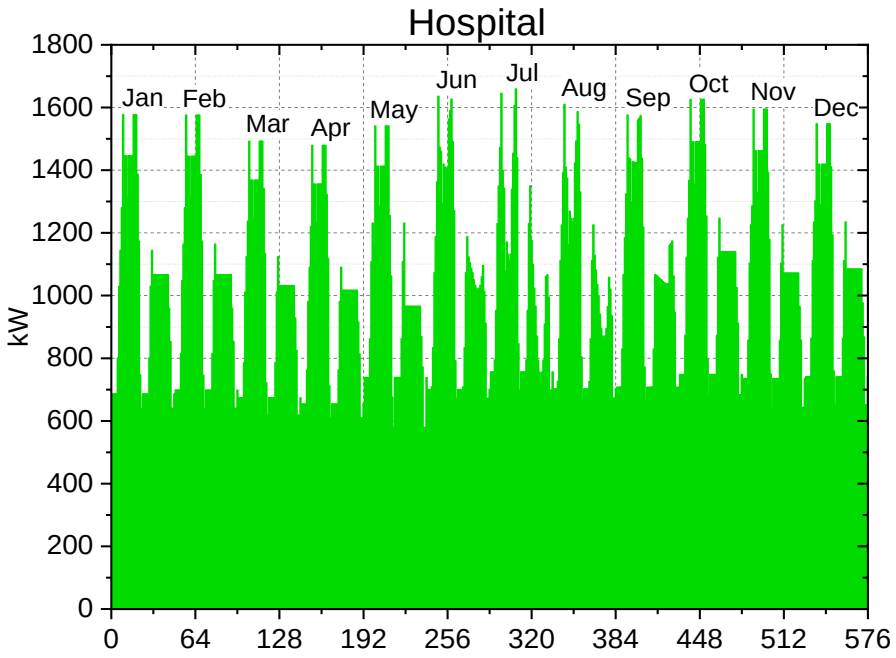


Figure S7. Annual electricity demand profiles (two 24-hours typical days per month) for the Hospital.

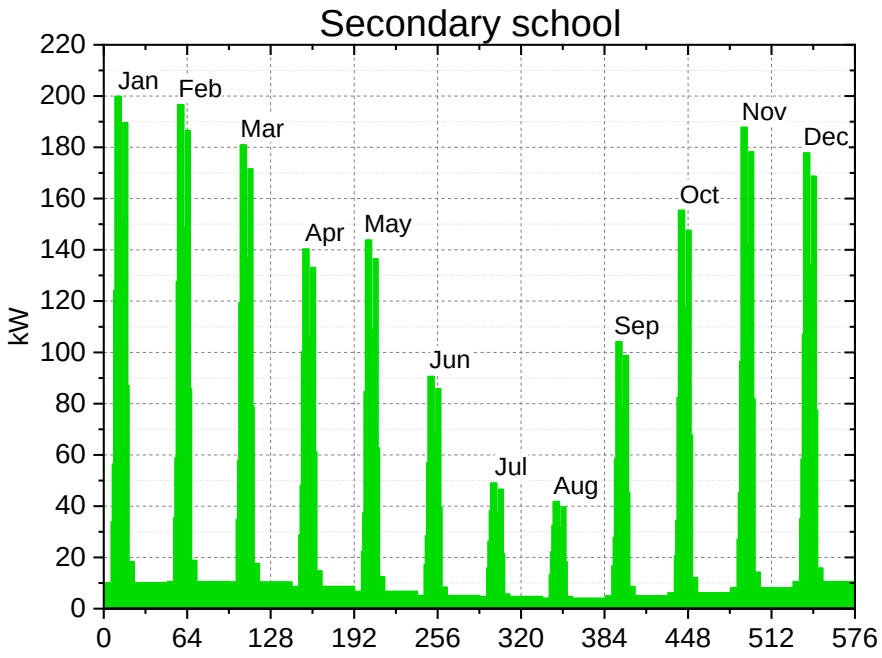


Figure S8. Annual electricity demand profiles (two 24-hours typical days per month) for the Secondary school.

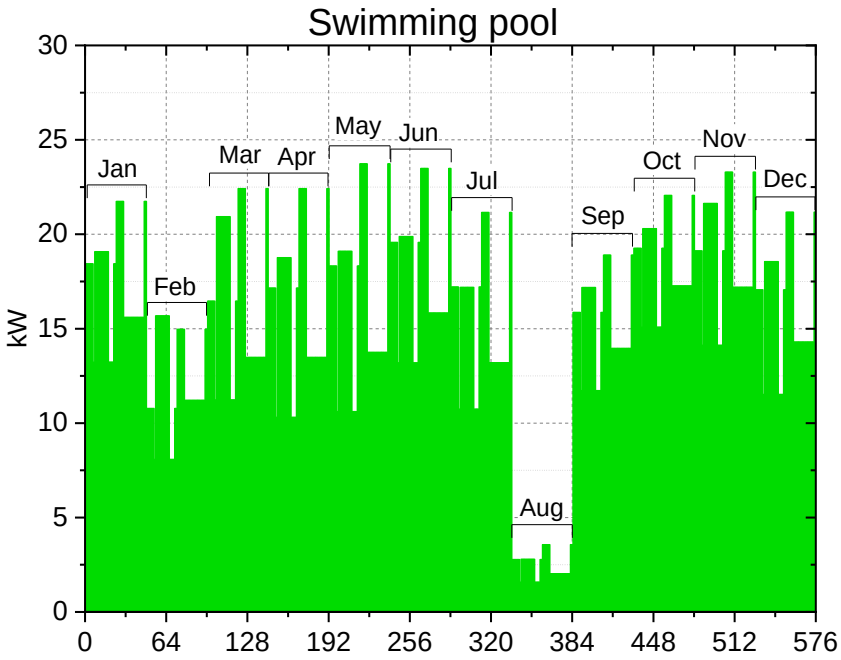


Figure S9. Annual electricity demand profiles (two 24-hours typical days per month) for the Swimming pool.

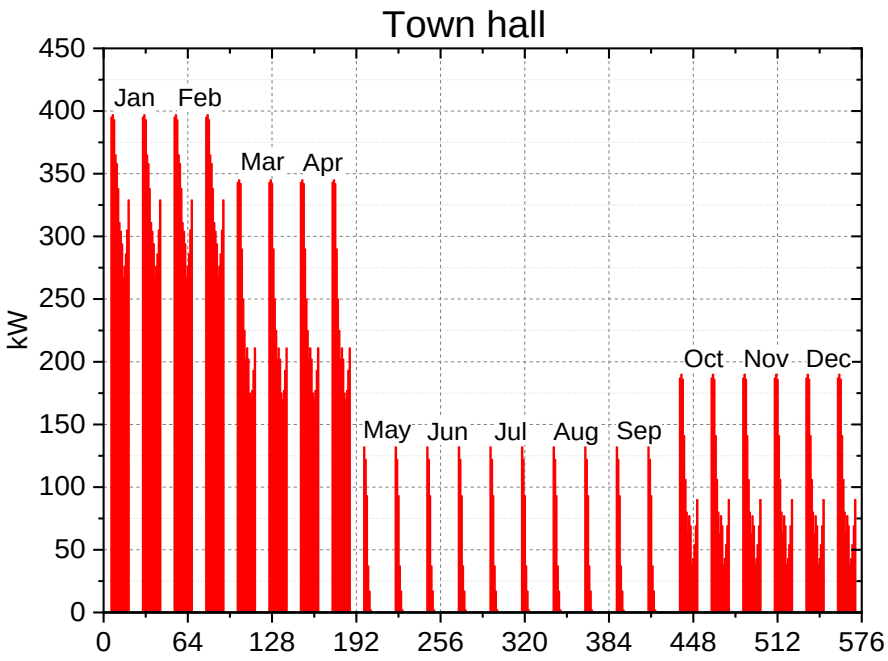


Figure S10. Annual heating demand profiles (two 24-hours typical days per month) for the Town hall.

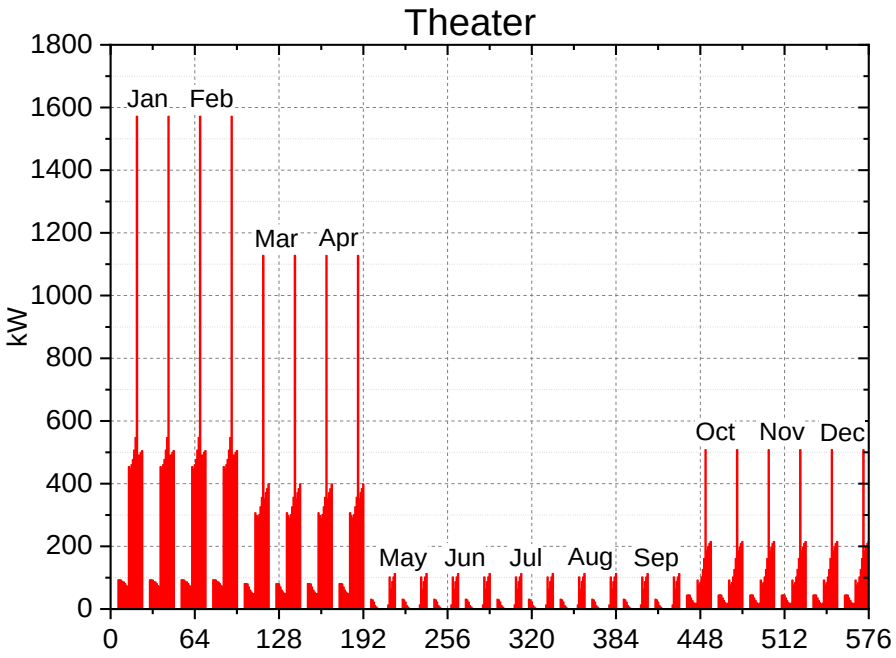


Figure S11. Annual heating demand profiles (two 24-hours typical days per month) for the Theater.

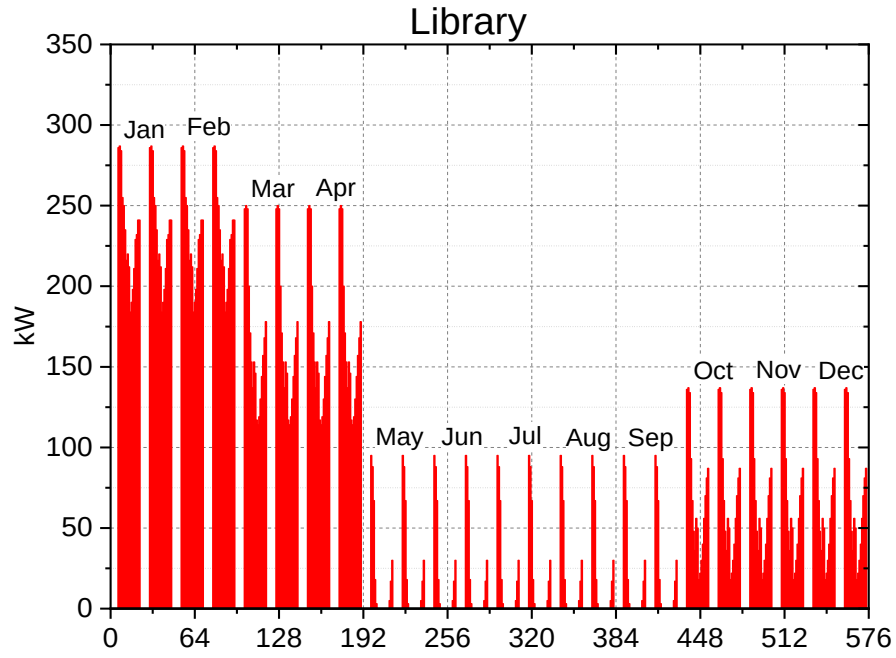


Figure S12. Annual heating demand profiles (two 24-hours typical days per month) for the Library.

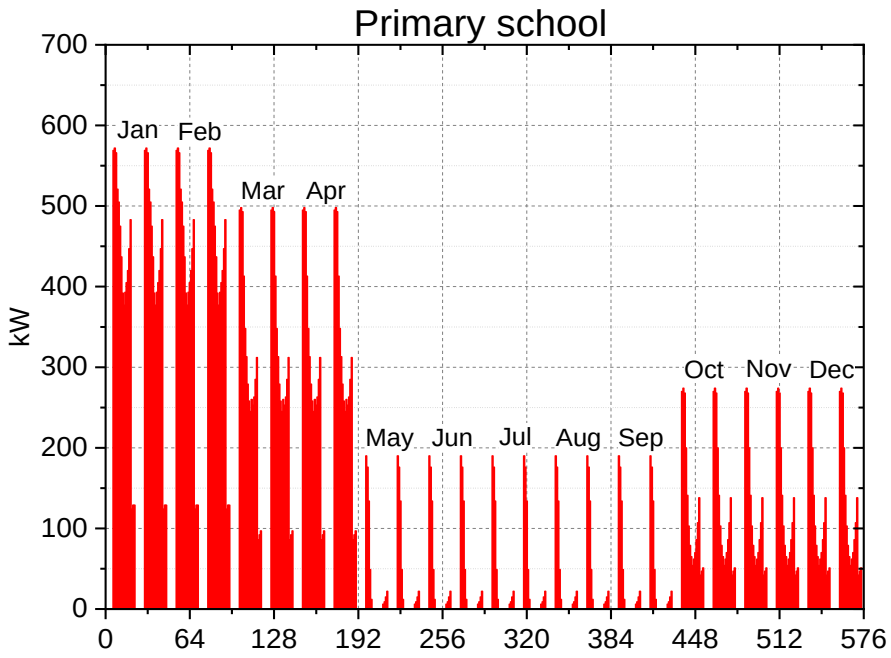


Figure S13. Annual heating demand profiles (two 24-hours typical days per month) for the Primary school.

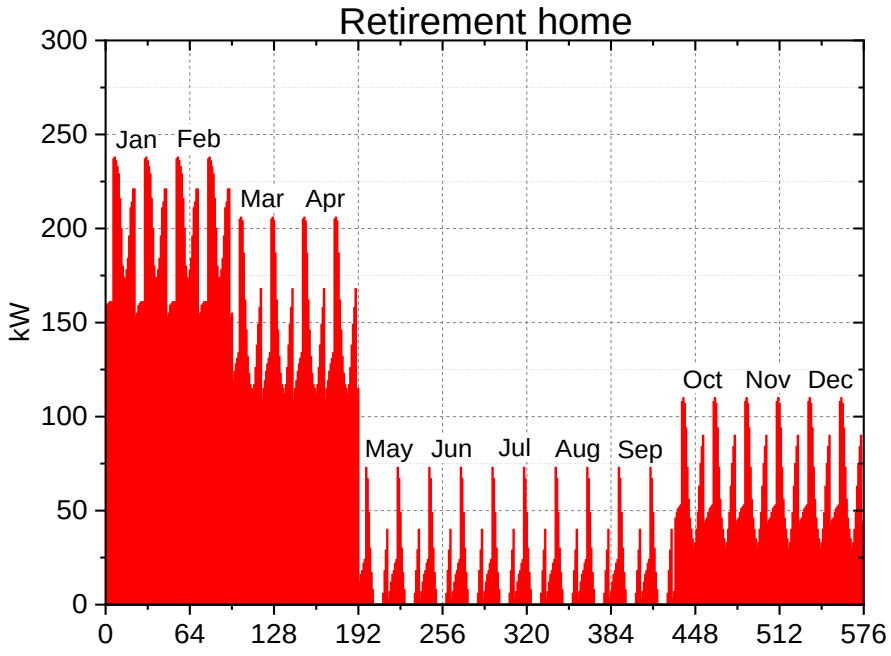


Figure S14. Annual heating demand profiles (two 24-hours typical days per month) for the Retirement home.

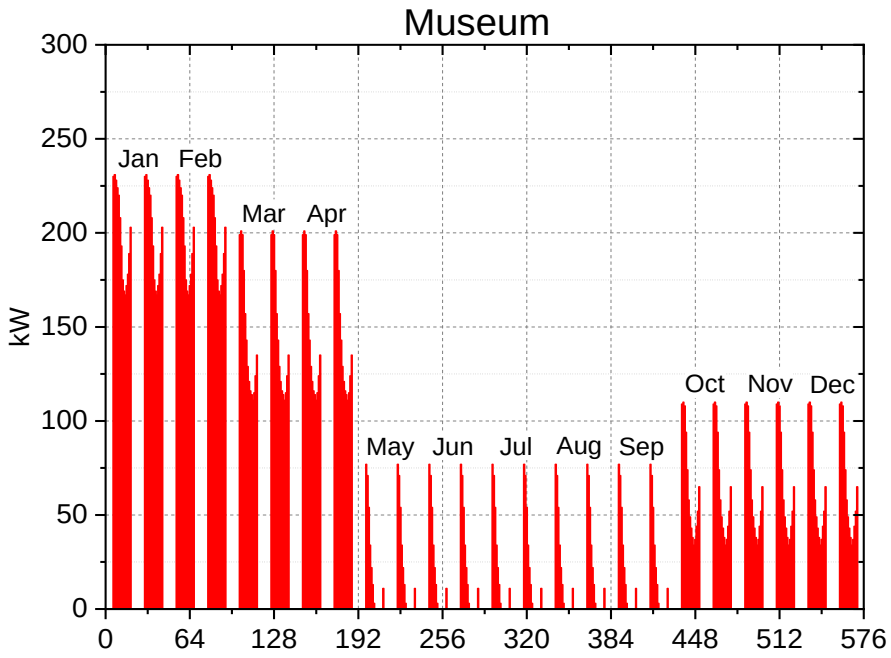


Figure S15. Annual heating demand profiles (two 24-hours typical days per month) for the Museum.

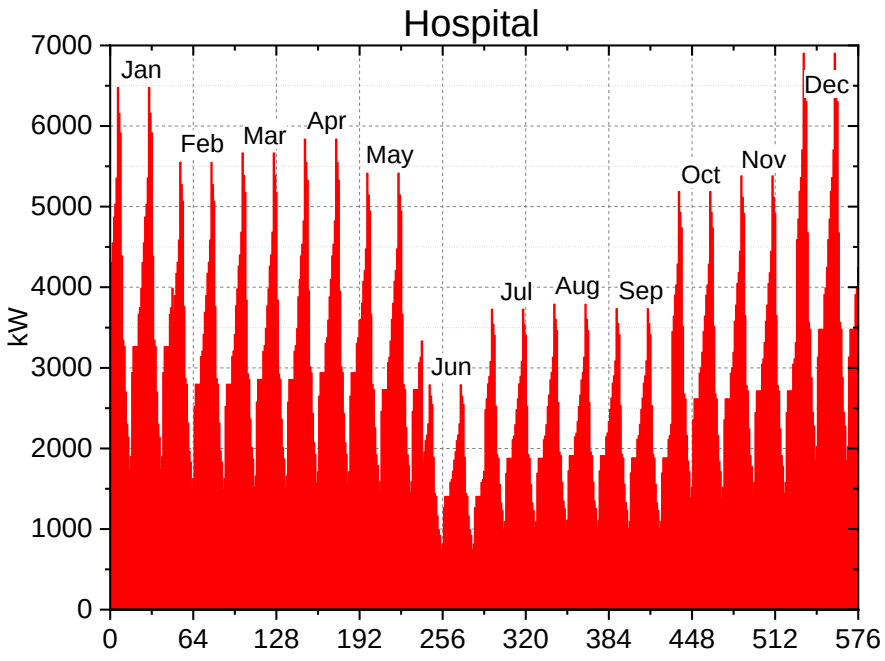


Figure S16. Annual heating demand profiles (two 24-hours typical days per month) for the Hospital.

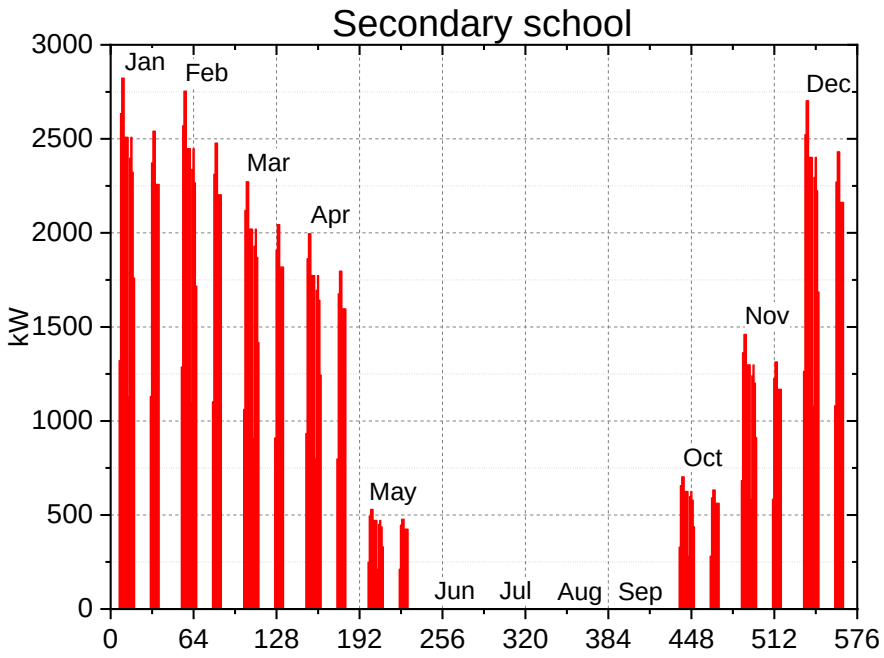


Figure S17. Annual heating demand profiles (two 24-hours typical days per month) for the Secondary school.

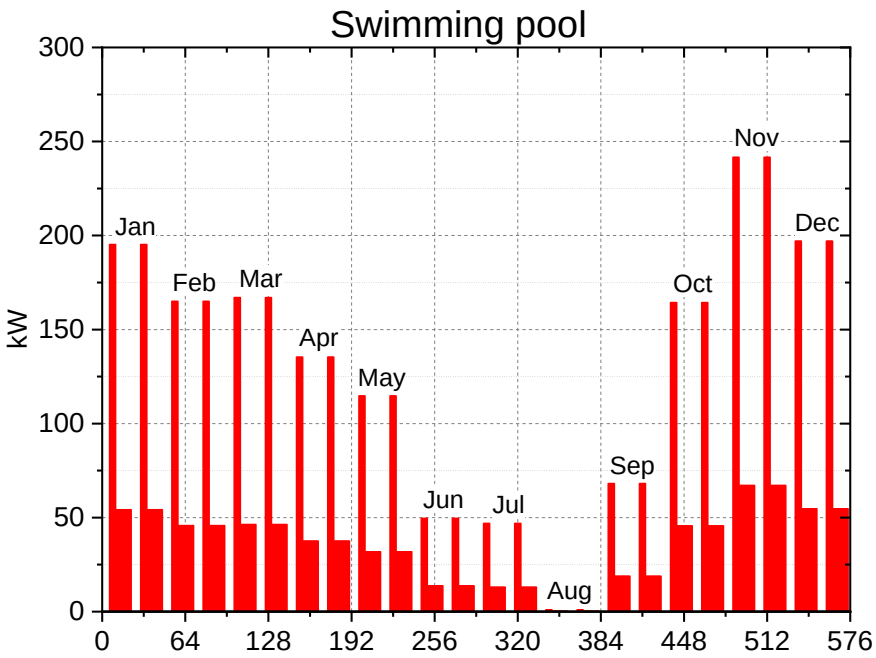


Figure S18. Annual heating demand profiles (two 24-hours typical days per month) for the Swimming pool.

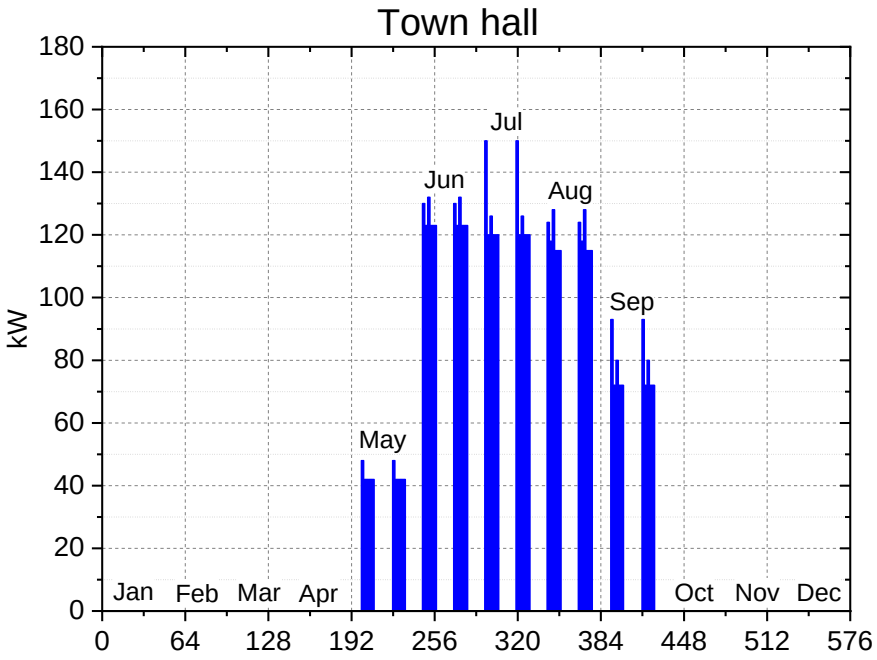


Figure S19. Annual cooling demand profiles (two 24-hours typical days per month) for the Town hall.

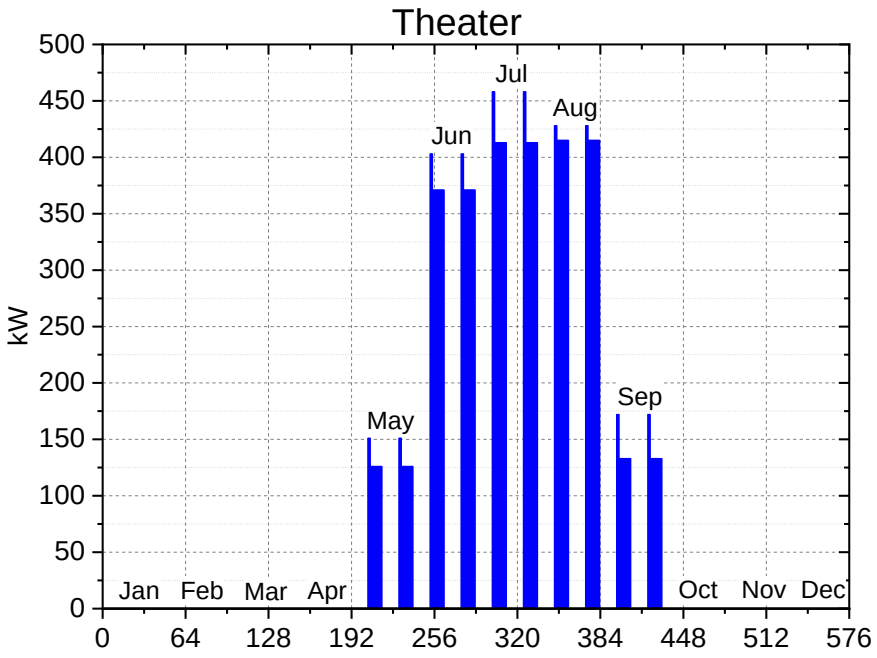


Figure S20. Annual cooling demand profiles (two 24-hours typical days per month) for the Theater.

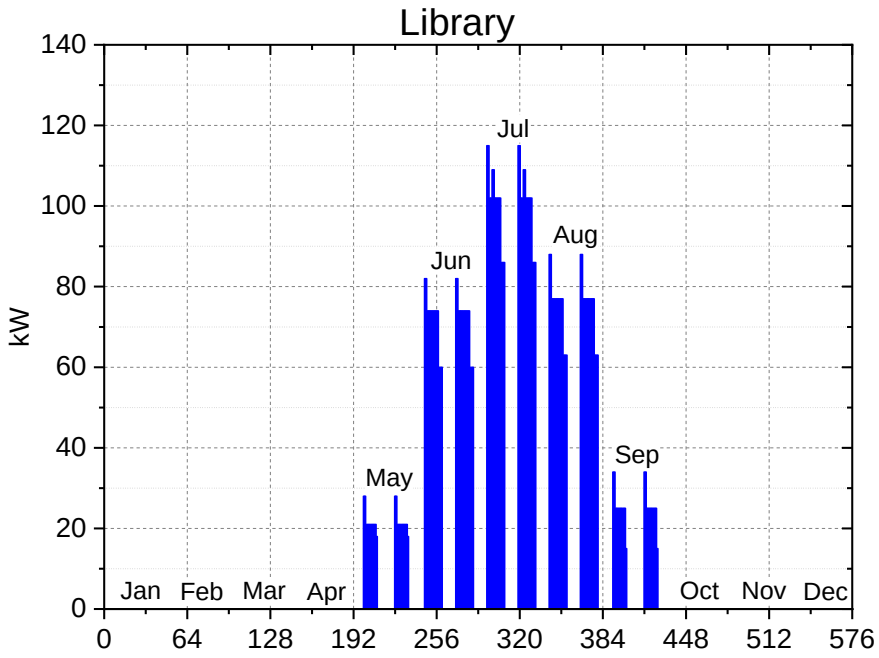


Figure S21. Annual cooling demand profiles (two 24-hours typical days per month) for the Library.

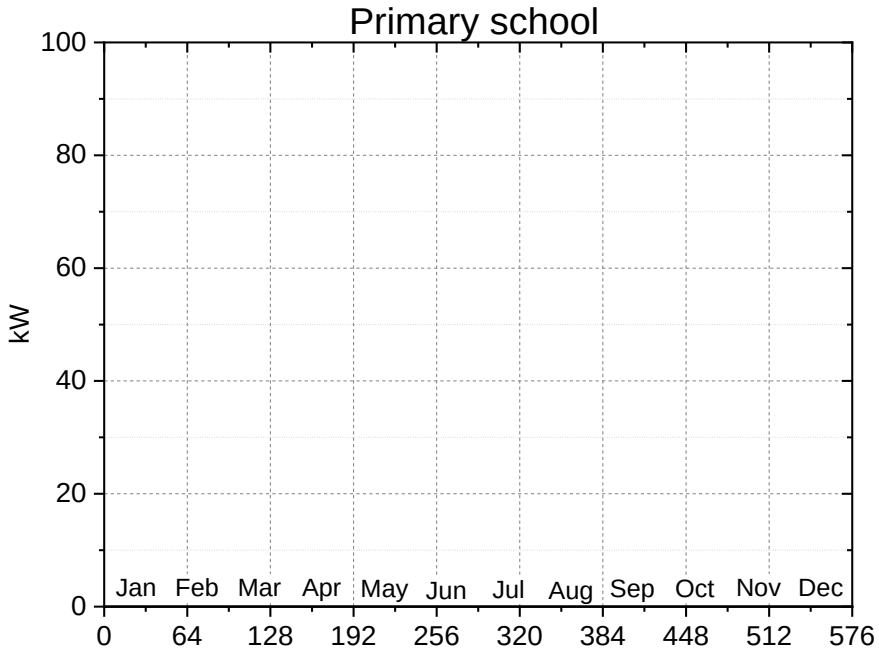


Figure S22. Annual cooling demand profiles (two 24-hours typical days per month) for the Primary school.

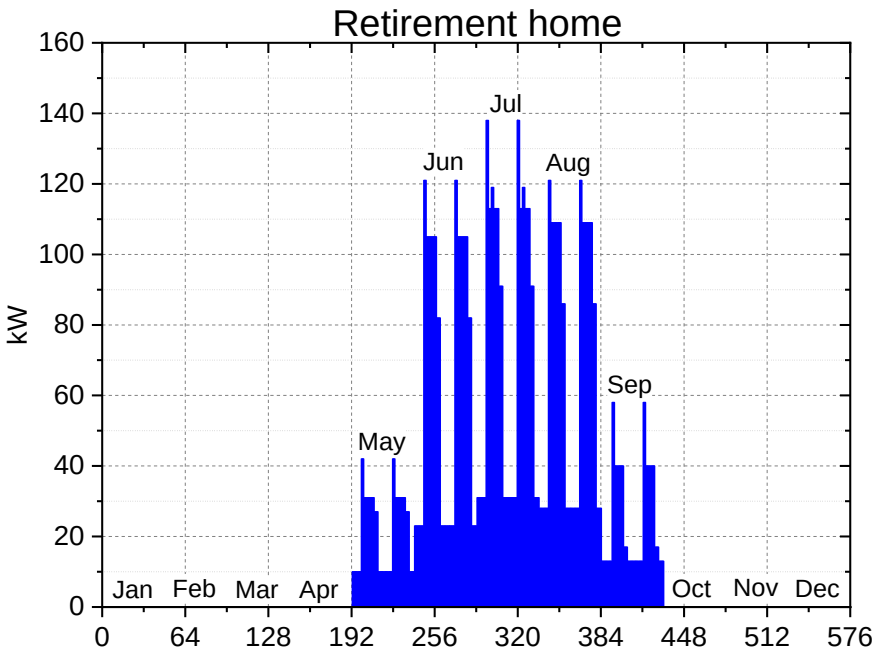


Figure S23. Annual cooling demand profiles (two 24-hours typical days per month) for the Retirement home.

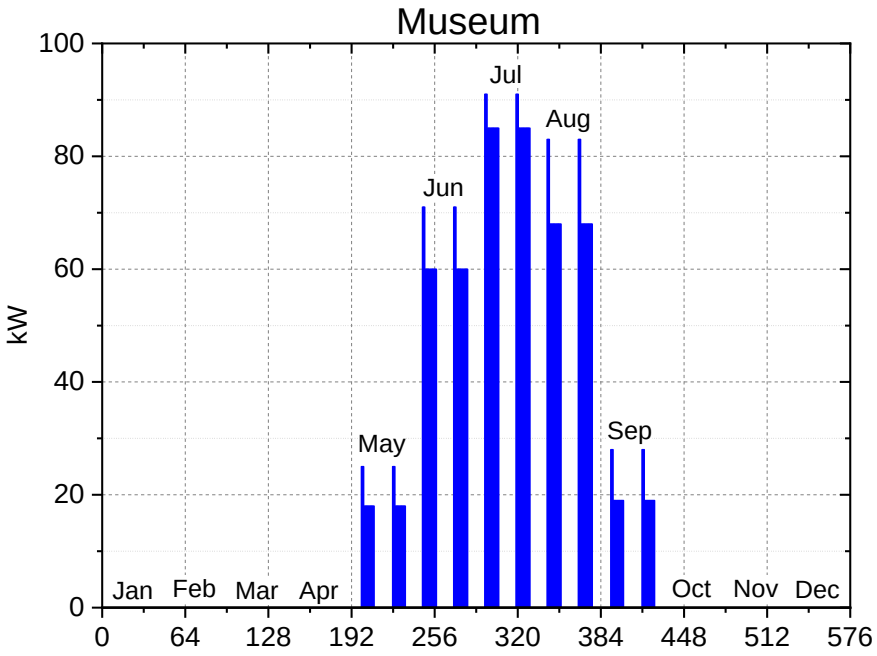


Figure S24. Annual cooling demand profiles (two 24-hours typical days per month) for the Museum.

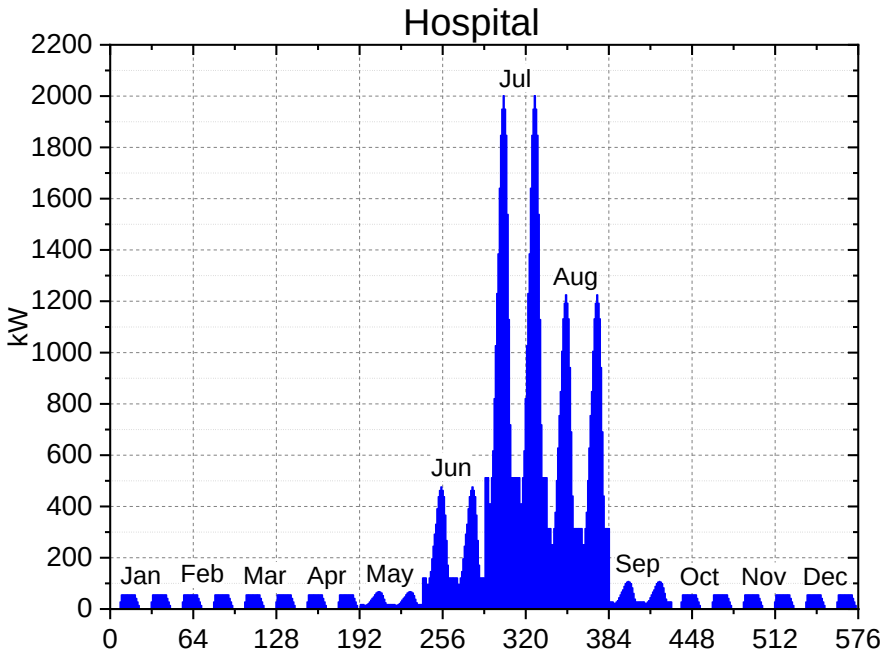


Figure S25. Annual cooling demand profiles (two 24-hours typical days per month) for the Hospital.

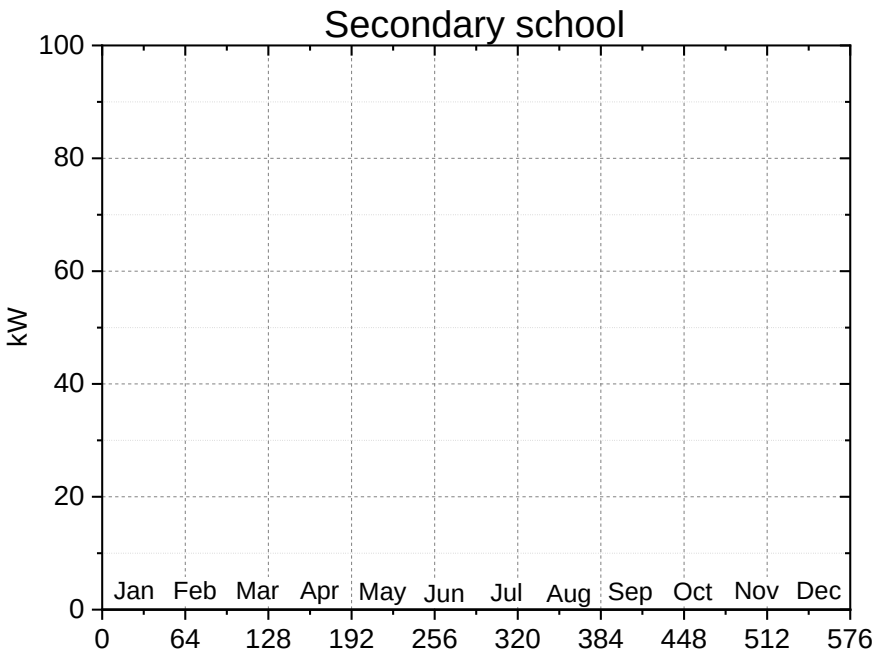


Figure S26. Annual cooling demand profiles (two 24-hours typical days per month) for the Secondary school.

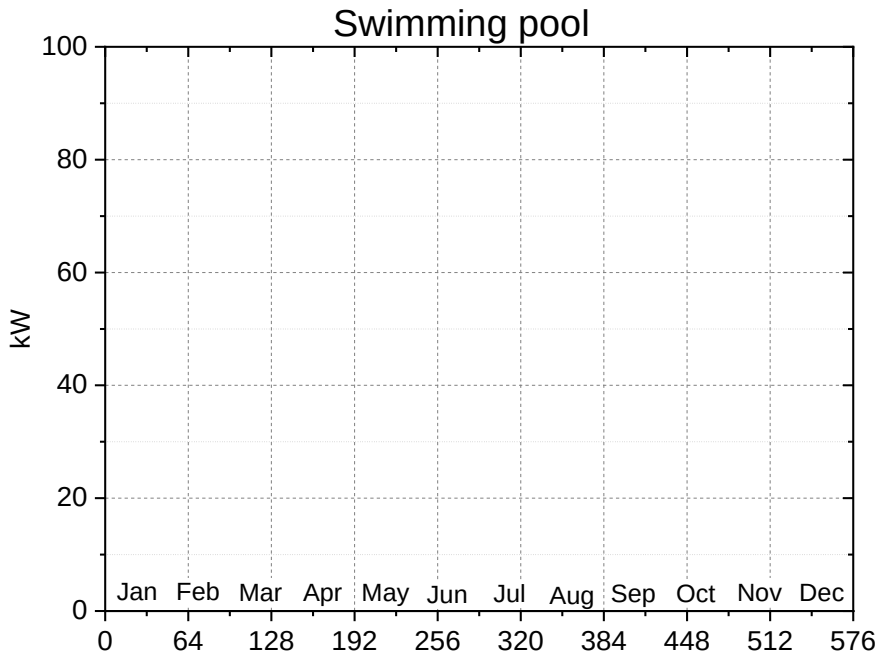


Figure S27. Annual cooling demand profiles (two 24-hours typical days per month) for the Swimming pool.

2. Technical data

This section presents the main technical data regarding some of the technologies considered for the superstructure of each EC building. The technologies not presented in this section, are fully described in the section 3.3 of the paper.

2.1 Internal combustion engine (ICE)

The considered ICE technical input data is based on real technology available on the market. According to the energy demand level, the buildings are allowed to install up to six engines of one of the four ICE sizes: EM-50/81, EM-70/115, EM-140/207, or EM-199/263. These ICE units are similar to the one shown in Figure S28 and are manufactured by [3].



Figure S28. Internal combustion engine. Vitobloc 200 (EM-50/81) [3].

Table S1 shows the technical data obtained from the Viessmann catalogues of the four ICE models. As observed, the data correspond to the equipment working at full load, as well as at partial load (30%, 50%, and 75%). Then, Table S2 provides the linear coefficients obtained from the data shown in Table 1.

Table S1. Technical data regarding the four ICE models from [3].

ICE model	Power (kW)	Heat (kW)	Fuel (kW)	Power efficiency	Total CHP efficiency
EM-50/81	15.00	30.82	62.81	0.24	0.73
	25.00	46.00	86.00	0.29	0.83
	38.00	64.00	118.00	0.32	0.86
	50.00	83.00	145.00	0.34	0.92
EM-70/115	21.00	43.32	87.56	0.24	0.73
	35.00	66.00	122.00	0.29	0.83
	53.00	85.00	159.00	0.33	0.87
	70.00	117.00	204.00	0.34	0.92
EM-140/207	42.00	98.90	165.70	0.25	0.85
	70.00	130.00	227.00	0.31	0.88
	105.00	171.00	310.00	0.34	0.89
	140.00	209.00	384.00	0.36	0.91
EM-199/263	57.00	142.59	214.46	0.27	0.93
	95.00	180.00	301.00	0.32	0.91
	143.00	235.00	408.00	0.35	0.93
	190.00	278.00	516.00	0.37	0.91

Table S2. Linear coefficients for the linearized equations derived from the ICE performance data (Table S1).

ICE model	Fuel x Power		Heat x Power	
	$kf_{ICE}(t,B,1)$	$kf_{ICE}(t,B,2)$	$kh_{ICE}(t,B,1)$	$kh_{ICE}(t,B,2)$
EM-50/81	2.362	27.379	1.479	8.637
EM-70/115	2.340	38.423	1.453	12.798
EM-140/207	2.243	71.502	1.129	51.501
EM-199/263	2.263	85.471	1.032	83.771

2.2 Micro gas turbine (MGT)

The MGT technical input data is also based on real technology available on the market. According to the energy demand level, the buildings are allowed to install up to six turbines of one of the four MGT sizes: C30, C65, T100, or C200. These MGT units are similar to the one shown in Figure S29 and are manufactured by [4].

Table S3. Technical data regarding the four MGT models from [4].

Capstone	Power [kW]	Heat [kW]	Fuel [kW]	Power efficiency	Total CHP efficiency
C30	9.23	27.79	47.89	0.19	0.77
	13.85	35.69	64.08	0.22	0.77
	18.46	42.06	78.30	0.24	0.77
	23.08	48.24	92.26	0.25	0.77
	27.69	54.92	106.88	0.26	0.77
	30.00	59.19	115.38	0.26	0.77
C65	20.00	52.37	93.02	0.22	0.78
	30.00	66.85	124.48	0.24	0.78
	40.00	78.33	152.09	0.26	0.78
	50.00	89.43	179.21	0.28	0.78
	60.00	101.52	207.61	0.29	0.78
	65.00	109.38	224.14	0.29	0.78
T100	30.77	73.92	138.34	0.22	0.76
	46.15	93.94	185.13	0.25	0.76
	61.54	109.63	226.19	0.27	0.76
	76.92	124.76	266.52	0.29	0.76
	92.31	141.34	308.76	0.30	0.76
	100.00	152.25	333.33	0.30	0.76
C200	61.54	113.53	251.53	0.24	0.70
	92.31	141.96	336.59	0.27	0.70
	123.08	163.15	411.25	0.30	0.70
	153.85	183.42	484.58	0.32	0.70
	184.62	206.10	561.38	0.33	0.70
	200.00	221.82	606.06	0.33	0.70

Table S3 shows the technical data obtained from the Capstone catalogues of the four MGT models. Then, Table 4 provides the linear coefficients obtained from the data shown in Table S3.



Figure S29. Micro gas turbine Capstone C65 [4].

Table S4. Linear coefficients for the linearized equations derived from the MGT performance data.

ICE model	Fuel x Power		Heat x Power	
	$kf_{ICE}(t,B,1)$	$kf_{ICE}(t,B,2)$	$kh_{ICE}(t,B,1)$	$kh_{ICE}(t,B,2)$
EM-50/81	2.362	27.379	1.479	8.637
EM-70/115	2.340	38.423	1.453	12.798
EM-140/207	2.243	71.502	1.129	51.501
EM-199/263	2.263	85.471	1.032	83.771

2.3 Absorption chiller (ABS)

According to the manufacturer's datasheet [5], the equipment can be used for several applications including cogeneration, solar cooling, and district heating. The selected models were WFC-SC10, WFC-SC20, and WFC-SC30, which have a nominal cooling capacity (NCC) of 35 kW, 70 kW, and 105 kW, respectively. The single-effect absorption cycle works with the working fluid pair lithium bromide/water, is fed by hot water ranging from 70 °C to 95 °C, and the condenser circuit is cooled by water from a cooling tower. The mentioned models are similar to the one shown in Figure S30.



Figure S30. Water fired Absorption Chiller WFC series [5].

Table S5 to Table S7 present the technical data regarding the adopted ABS models. Such data represent the performance characteristics for a cooling power supply at the temperature of 7 °C. As observed in the tables, the ABS performance depends on the Cooling Water Temperature (CWT), which is the water circuit coming from the cooling tower to remove heat from the absorber and condenser. As expected, the higher this temperature the lower the ABS COP, although there is not a substantial variation. The equipment is designed to provide the nominal cooling capacity when the cooling capacity factor (CCF) is equal to 1. As the CWT increases, the heat medium inlet temperature (HMIT) should be higher in order for the ABS achieve the nominal cooling capacity. A variation in the HMIT results a corresponding variation on the cooling capacity of the ABS. Therefore, it was assumed that the ABS operation range is $ABS_{max} = NCC$ and $ABS_{min} = (1/3)\ NCC$, while the COP are the ones presented in Table S4 of the paper.

Table S5. Technical data from the ABS manufacturer [5] for the model WFC-SC10. Nominal cooling capacity: 35.2 kW; Heat input: 50.2 kW. Abbreviations: Heat Medium Inlet Temperature (HMIT), Cooling Capacity Factor (CCF), Heat Input Factor (HIF).

WFC-SC10					
HMIT [ºC]	**CCF**	**HIF**	**Cooling [kW]**	**Heat input [kW]**	**COP**
Cooling Water Temperature at 27 ºC					
72.50	0.68	0.65	23.94	32.63	0.73
75.00	0.80	0.73	28.16	36.65	0.77
77.50	0.90	0.82	31.68	41.16	0.77
80.00	1.00	0.95	35.20	47.69	0.74
82.50	1.10	1.07	38.72	53.71	0.72
85.00	1.20	1.18	42.24	59.24	0.71
87.50	1.29	1.28	45.41	64.26	0.71
90.00	1.34	1.36	47.17	68.27	0.69
92.50	1.38	1.44	48.58	72.29	0.67
95.00	1.40	1.49	49.28	74.80	0.66
Cooling Water Temperature at 29.5 ºC					
72.50	0.40	0.44	14.08	22.09	0.64
75.00	0.52	0.53	18.30	26.61	0.69
77.50	0.65	0.63	22.88	31.63	0.72
80.00	0.77	0.73	27.10	36.65	0.74
82.50	0.89	0.87	31.33	43.67	0.72
85.00	1.00	0.98	35.20	49.20	0.72
87.50	1.10	1.10	38.72	55.22	0.70
90.00	1.19	1.19	41.89	59.74	0.70
92.50	1.23	1.27	43.30	63.75	0.68
95.00	1.25	1.32	44.00	66.26	0.66
Cooling Water Temperature at 31 ºC					
72.50	0.33	0.32	11.62	16.06	0.72
75.00	0.45	0.41	15.84	20.58	0.77
77.50	0.60	0.51	21.12	25.60	0.82
80.00	0.70	0.64	24.64	32.13	0.77
82.50	0.82	0.78	28.86	39.16	0.74
85.00	0.92	0.89	32.38	44.68	0.72
87.50	1.00	1.00	35.20	50.20	0.70
90.00	1.05	1.10	36.96	55.22	0.67
92.50	1.08	1.20	38.02	60.24	0.63
95.00	1.10	1.25	38.72	62.75	0.62

Table S6. Technical data from the ABS manufacturer [5] for the model WFC-SC20. Nominal cooling capacity: 70.3 kW; Heat input: 100 kW. Abbreviations: Heat Medium Inlet Temperature (HMIT), Cooling Capacity Factor (CCF), Heat Input Factor (HIF).

WFC-SC20					
HMIT [ºC]	**CCF**	**HIF**	**Cooling [kW]**	**Heat input [kW]**	**COP**
Cooling Water Temperature at 27 ºC					
72.50	0.66	0.60	46.40	60.00	0.77
75.00	0.75	0.69	52.73	69.00	0.76
77.50	0.84	0.77	59.05	77.00	0.77
80.00	0.95	0.87	66.79	87.00	0.77
82.50	1.04	0.95	73.11	95.00	0.77
85.00	1.12	1.07	78.74	107.00	0.74
87.50	1.18	1.19	82.95	119.00	0.70
90.00	1.20	1.27	84.36	127.00	0.66
92.50	1.21	1.33	85.06	133.00	0.64
95.00	1.22	1.38	85.77	138.00	0.62
Cooling Water Temperature at 29.5 ºC					
72.50	0.46	0.42	32.34	42.00	0.77
75.00	0.60	0.51	42.18	51.00	0.83
77.50	0.73	0.61	51.32	61.00	0.84
80.00	0.82	0.71	57.65	71.00	0.81
82.50	0.91	0.84	63.97	84.00	0.76
85.00	1.00	0.96	70.30	96.00	0.73
87.50	1.07	1.06	75.22	106.00	0.71
90.00	1.10	1.14	77.33	114.00	0.68
92.50	1.12	1.21	78.74	121.00	0.65
95.00	1.14	1.26	80.14	126.00	0.64
Cooling Water Temperature at 31 ºC					
72.50	0.35	0.31	24.61	31.00	0.79
75.00	0.49	0.41	34.45	41.00	0.84
77.50	0.60	0.51	42.18	51.00	0.83
80.00	0.71	0.63	49.91	63.00	0.79
82.50	0.81	0.75	56.94	75.00	0.76
85.00	0.91	0.88	63.97	88.00	0.73
87.50	1.00	0.99	70.30	99.00	0.71
90.00	1.05	1.09	73.82	109.00	0.68
92.50	1.08	1.16	75.92	116.00	0.65
95.00	1.09	1.20	76.63	120.00	0.64

Table S7. Technical data from the ABS manufacturer [5] for the model WFC-SC30. Nominal cooling capacity: 105.6 kW; Heat input: 151 kW. Abbreviations: Heat Medium Inlet Temperature (HMIT), Cooling Capacity Factor (CCF), Heat Input Factor (HIF).

WFC-SC30					
HMIT [ºC]	**CCF**	**HIF**	**Cooling [kW]**	**Heat input [kW]**	**COP**
Cooling Water Temperature at 27 ºC					
72.50	0.70	0.62	73.92	93.62	0.79
75.00	0.80	0.75	84.48	113.25	0.75
77.50	0.89	0.88	93.98	132.88	0.71
80.00	0.97	0.97	102.43	146.47	0.70
82.50	1.05	1.07	110.88	161.57	0.69
85.00	1.13	1.16	119.33	175.16	0.68
87.50	1.20	1.25	126.72	188.75	0.67
90.00	1.26	1.33	133.06	200.83	0.66
92.50	1.30	1.40	137.28	211.40	0.65
95.00	1.34	1.45	141.50	218.95	0.65
Cooling Water Temperature at 29.5 ºC					
72.50	0.41	0.42	43.30	63.42	0.68
75.00	0.54	0.54	57.02	81.54	0.70
77.50	0.66	0.65	69.70	98.15	0.71
80.00	0.78	0.77	82.37	116.27	0.71
82.50	0.90	0.87	95.04	131.37	0.72
85.00	0.99	0.98	104.54	147.98	0.71
87.50	1.07	1.09	112.99	164.59	0.69
90.00	1.13	1.20	119.33	181.20	0.66
92.50	1.18	1.30	124.61	196.30	0.63
95.00	1.21	1.34	127.78	202.34	0.63
Cooling Water Temperature at 31 ºC					
72.50	0.26	0.31	27.46	46.81	0.59
75.00	0.40	0.42	42.24	63.42	0.67
77.50	0.55	0.55	58.08	83.05	0.70
80.00	0.69	0.68	72.86	102.68	0.71
82.50	0.81	0.79	85.54	119.29	0.72
85.00	0.92	0.90	97.15	135.90	0.71
87.50	1.00	1.00	105.60	151.00	0.70
90.00	1.06	1.10	111.94	166.10	0.67
92.50	1.10	1.19	116.16	179.69	0.65
95.00	1.13	1.25	119.33	188.75	0.63

2.4 Heat pump (HP)

The adopted HP technologies are manufactured by Daikin [6] and similar to the one shown in Figure 31. They are air cooled multiple scroll chillers that, according to the manufacturer,

provide a better partial load efficiency. The adopted models are EUWY-KBZW1, EWYQ-DAYNN080, and EWYQ-DAYNN100 with cooling/heating capacities of 35 kW, 80 kW, and 100 kW, respectively.



Figure S31. Heat pump EWYQ-DAYN [6].

Table S8 shows the COP values for each adopted HP model and for different values of ambient temperature. As observed, the performance of the equipment is considerably affected by the ambient temperature and whether it is working under heating or cooling mode.

It should be noted that, in the case of heating mode, the HP works to overcome a ΔT between 30 °C (when the ambient temperature is 20 °C) and 50 °C (when the ambient temperature is 0 °C). For this reason, the COP values tend to be lower when compared to a scenario where the same HP (still in heating mode) works to overcome a ΔT around 20 °C. When it comes to the cooling mode, the HP should overcome a ΔT between 10 °C and 25 °C, which results in higher levels of cooling production with a lower level of power input. As a consequence, this operation mode provides higher levels of COP.

Table S8. Technical data regarding the three adopted HP models [6].

Operation mode	Ambient temperature [°C]	Nominal capacity [kW]	COP
Heating	0	35	2.17
		80	2.26
		100	2.30
	4	35	2.31
		80	2.45
		100	2.51
	10	35	2.61
		80	2.72
		100	2.77
	15	35	2.90
		80	2.96
		100	2.99
	21	35	3.10
		80	3.21
		100	3.27
Cooling	20	35	4.90
		80	4.63
		100	4.51
	25	35	4.40
		80	4.09
		100	3.95
	30	35	4.00
		80	3.59
		100	3.40
	35	35	3.50
		80	3.12
		100	2.94

2.5 Solar technologies

The solar technologies regard photovoltaic (PV) panels and solar thermal (ST) panels. The energy production from both types of technologies was obtained by using the System Advisor Model (SAM) software [7]. The production for both PV and ST were calculated per square meter of the installed technology. Table S9 and Table S10 provide the hourly energy production by PV and ST, respectively.

Table S9. Hourly photovoltaic (PV) specific energy production ($k_{PV}(t)$), in W/m^2.

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.18	1.35	4.87	3.25	0.93	0.00	0.00	0.00	0.00
7	0.00	0.00	1.01	4.32	3.89	16.66	11.75	10.39	5.28	0.26	0.00	0.00
8	0.00	3.77	17.78	14.52	16.01	42.37	36.96	30.35	23.34	11.38	2.00	0.00
9	17.13	29.73	41.93	31.62	30.12	67.62	61.41	59.78	46.56	20.85	13.55	16.96
10	32.00	36.83	68.61	49.92	48.59	84.97	83.06	81.46	61.47	36.06	18.72	35.39
11	40.36	63.53	90.79	58.77	55.48	98.96	90.94	96.61	81.89	46.52	26.47	38.64
12	56.96	72.78	97.96	73.11	67.91	111.20	97.49	105.84	88.21	55.30	27.62	40.90
13	65.52	88.75	97.98	76.41	59.09	114.59	95.68	114.38	85.58	61.49	28.58	44.48
14	48.54	79.01	88.67	68.67	57.62	107.64	89.54	102.41	70.57	52.14	27.95	36.82
15	40.23	69.15	71.41	60.88	46.12	95.52	71.68	91.08	64.52	42.28	20.12	33.63
16	25.77	46.74	58.76	42.67	39.97	75.53	57.56	60.10	44.56	23.50	6.34	15.60
17	3.68	22.52	32.54	30.46	27.60	53.91	42.48	40.42	29.74	10.20	0.20	0.00
18	0.00	0.76	8.41	10.99	13.29	27.04	19.80	16.48	7.26	0.10	0.00	0.00
19	0.00	0.00	0.00	1.20	3.55	7.11	5.59	3.31	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	1.07	0.46	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S10. Hourly solar thermal (ST) specific energy production ($k_{ST}(t)$), in W/m^2.

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	2.83	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	3.26	11.87	37.52	26.19	11.62	0.00	0.00	0.00	0.00
7	0.00	0.00	6.93	20.58	22.29	64.78	52.07	49.39	24.12	2.95	0.00	0.00
8	0.00	9.48	30.34	41.47	64.14	104.62	96.39	92.54	51.97	23.08	5.88	0.00
9	15.87	32.77	183.68	171.67	169.77	393.24	353.78	334.20	252.10	107.29	44.05	15.11
10	161.79	198.65	383.53	290.23	284.16	532.85	517.61	488.25	366.18	203.44	98.83	177.43
11	219.46	371.15	539.13	354.08	334.65	651.38	589.34	605.78	521.11	273.45	149.43	210.76
12	318.77	434.80	602.05	448.14	416.25	745.92	643.17	684.82	570.57	329.50	156.81	228.22
13	372.24	549.49	604.67	465.20	359.06	766.61	634.63	739.79	549.32	360.57	158.27	249.16
14	267.12	472.04	531.66	413.14	344.28	706.95	582.86	651.97	445.06	301.23	155.66	200.06
15	214.67	397.03	412.50	357.38	268.39	605.24	447.25	563.60	386.95	233.95	103.83	173.46
16	94.08	243.98	315.13	237.16	226.82	452.24	343.32	348.65	247.09	105.35	15.95	16.84
17	8.71	34.53	48.88	83.86	88.57	118.40	119.62	109.33	61.93	26.87	2.04	0.00
18	0.00	4.05	24.00	42.74	57.77	89.00	74.36	64.98	27.43	1.32	0.00	0.00
19	0.00	0.00	0.00	12.33	25.47	49.80	38.69	26.67	1.48	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	1.89	14.93	8.74	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S11 provides the main input parameters specified in the SAM simulations for calculating the hourly energy productions by PV and ST panels. Most of the data are automatically updated when the location is specified. For what concerns ST panels, the input parameters as well as the hourly energy productions were considered the same for ST panels installed on the buildings or in the central unit.

Table S11. Main input parameters (to SAM software [7]) to simulate the hourly energy production from PV and ST panels. Abbreviations: Annual average (AA), Collector heat removal factor ($\boldsymbol{F_R}$), Transmittance and Absorptance ($\boldsymbol{\tau\alpha}$), Heat loss coefficient ($\boldsymbol{U_L}$), Incidence Angle Modifier (IAM).

Parameter	Value	Unit
Shared parameters (PV and ST)		
Location	Pordenone	-
Latitude	45.97	degrees
Longitude	12.66	degrees
AA global horizontal	3.77	kWh/m^2/day
AA direct normal (beam)	4.02	kWh/m^2/day
AA diffuse horizontal	1.52	kWh/m^2/day
AA temperature	14.6	°C
Array type	Fixed roof mount	-
Tilt	30	degrees
Azimuth	180	degrees
PV		
Total loss	14	%
DC to AC ratio	1.15	-
Inverter efficiency	96	%
ST		
Working fluid	Water	-
$\boldsymbol{F_R(\tau\alpha)}$	0.689	-
$\boldsymbol{F_R U_L}$	3.85	W/m^2.°C
IAM coefficient	0.2	-
Water flow rate	0.046	kg/s

2.6 DHCN pipelines

Table S12 and Table S13 present the loss factors for heat and cooling pipelines, respectively. All non-zero values represent possible connections between the buildings.

Table S12. Dissipation factors regarding heat pipelines.

	Buildings								
From \ To	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	-	0.0225	0	0	0.0115	0.01	0	0	0
2	0.0225	-	0.004	0	0.0125	0.013	0	0	0
3	0	0.004	-	0.01	0	0	0	0	0
4	0	0	0.01	-	0	0	0.07	0.07	0
5	0.0115	0.0125	0	0	-	0.0015	0	0	0
6	0.01	0.013	0	0	0.0015	-	0	0	0
7	0	0	0	0.07	0	0	-	0	0.0125
8	0	0	0	0.09	0	0	0	-	0.02
9	0	0	0	0	0	0	0.0125	0.02	-

Table S13. Dissipation factors regarding cooling pipelines.

	Buildings								
From \ To	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	0	0.036	0	0	0.0184	0.016	0	0	0
2	0.036	0	0.0064	0	0.02	0.0208	0	0	0
3	0	0.0064	0	0.016	0	0	0	0	0
4	0	0	0.016	0	0	0	0.112	0.112	0
5	0.0184	0.02	0	0	0	0.0024	0	0	0
6	0.016	0.0208	0	0	0.0024	0	0	0	0
7	0	0	0	0.112	0	0	0	0	0.02
8	0	0	0	0.144	0	0	0	0	0.032
9	0	0	0	0	0	0	0.02	0.032	0

3. Economic data

3.1 Fixed costs plus maintenance factors

The investment costs and maintenance factors of the technologies comprising the building k, central unit, and DHCN pipelines superstructures are based on catalogues of commercially available devices as well as on the scientific literature. Table S14 provides the mentioned figures for each considered device.

MGT, ICE, ABS, and HP were selected based on different nominal capacities, according to the energy demand magnitude of each building. As observed in Table S14, the cost of the different nominal capacities (for the same technology) varies accordingly, although the maintenance factor has been considered the same for each nominal capacity. BOI, CC, PV, ST, HST, and

CST were not modelled considering fixed investment costs. Instead, their costs are based on the final installed capacity, i.e., these are variable costs, which are detailed on the next section.

Table S14. Investment costs and maintenance factors for the EC selected technologies.

Technologies	Fixed investment cost k€	Maintenance factor €/kWh
Building k superstructure		
ICE 50 kW_{el}	89	0.01
ICE 70 kW_{el}	103	
ICE 140 kW_{el}	185	
ICE 200 kW_{el}	245	
MGT 30 kW_{el}	74	0.002
MGT 65 kW_{el}	148	
MGT 100 kW_{el}	207	
MGT 200 kW_{el}	340	
ABS 35 kW_{c}	31	0.001
ABS 70 kW_{c}	60	
ABS 105 kW_{c}	89	
HP 35 kW_{el}	30	0.001
HP 80 kW_{el}	53	
HP 100 kW_{el}	78	
BOI	-	0.001
CC	-	0.002
PV	-	0
ST	-	0
HST	-	0
CST	-	0
Inst. DHCN pipeline	300	0
Central unit superstructure		
ICE	340	0.01
BOI	290	0.001
ST	-	0
HST	-	0
Inst. DHN pipeline	600	0

3.2 Variable costs

The hourly operation costs of the technologies comprising the building k, central unit, and DHCN pipelines superstructures were also based on catalogues of commercially available devices as well as on the scientific literature. Table S15 provides the variable costs for each considered device.

Table S15. Variable costs for the EC selected technologies.

Technologies	Variable investment cost
Building k superstructure	
BOI	80 €/kW_{th}
CC	150 €/kW_c
PV	250 €/m^2
ST	600 €/m^2
HST	20 €/kWh
CST	20 €/kWh
Installed DHCN pipeline	300 €/m 0.25 €/kW.m
Central unit superstructure	
ICE	990 €/kW_{el}
BOI	45 €/kW_{th}
ST	300 €/m^2
HST	5 €/kWh
Installed DHN pipeline	600 €/m 0.04 €/kW.m

3.3 Energy resources economic data

The prices reported on Table S11 (of the main paper) are based on the PUN (acronym for *Prezzo Unico Nazionale* or National Unique Price), which is the wholesale reference price of electricity that is purchased on the Italian Power Exchange (IPEX) market. The PUN prices data can be obtained as a monthly average value divided into three-hour bands (Table S16). The data was taken from a pre-pandemic period, in this case for 2019. Then, these bands are used to specify the hourly electricity price for each day, according to Table S17. Such specification is regulated by ARERA [8] and have different electricity prices: F1 (On-peak); F2 (Mid-level); and F3 (Off-peak).

Table S16. Monthly average PUN divided into three hour bands [9].

€/MWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
F1	76.64	61.79	55.61	59.2	53.6	54.02	57.64	51.54	57.4	60.17	57.73	53.03
F2	72.48	63.65	57.81	59.14	56.09	52.49	56.51	54.78	56.35	58.39	52.43	47.91
F3	58.46	51.11	48.15	46.7	45.64	42.65	45.59	45.18	43.96	43.7	39.17	35.33

Table S17. Hourly distribution of the time bands (F1, F2, and F3) for purchasing electricity, according to ARERA [8].

Hour	1	2	3	4	5	6	7	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mon	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Tue	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Wed	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Thu	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Fri	3	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3
Sat	3	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3
Sun	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Bearing in mind that the PUN value corresponds only to the electricity production cost, some calculations should be made in order to estimate what would be the electricity bill value, which is the actual electricity price input to the EC model. The calculation was procedure as follows: (i) according to ARERA [10], the percentages provided in Table S18 represent the portion of the final electricity bill value regarding the electricity production cost, (ii) as the PUN corresponds to the electricity production cost, it was divided by the mentioned percentages in order to obtain the estimated electricity prices.

Table S18. Portion of the final electricity price regarding electricity production cost (per trimester).

2019	Electricity price % regarding electricity production cost
Trimester I	49.8
Trimester II	42.3
Trimester III	43.9
Trimester IV	45.6

According to the *Deliberazione AEEG 280/07*, the considered time bands for the hourly selling electricity price is stablished as shown in Table S19, which is slightly different from Table S17. Then, the data regarding the selling electricity price was retrieved from GSE [11] for the north zone, as presented in Table S12 of the paper.

Table S19. Hourly distribution of the time bands (F1, F2, and F3) for selling electricity, according to GSE [12].

Hour	1	2	3	4	5	6	7	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Mon	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3
Tue	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3
Wed	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3
Thu	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3
Fri	3	3	3	3	3	3	2	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3
Sat	3	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3
Sun	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

4. Mathematical model

4.1 Objective function: complementary equations

The aim of this section is to provide some equations that, for the sake of briefness, were not presented in the paper. Such equations are the ones presented from Eq. (S1) to Eq. (S8), which are essential to understanding how the total annual operation cost (AOC_{tot}), total annual maintenance cost (AMC_{tot}), and total annual investment cost (AIC_{tot}) have been calculated (the reader may refer to Eq. (S2) to Eq. (S4) of the paper).

Equation (S1) shows the expression through which the operation cost regarding the central unit has been calculated. This cost comprises the hourly gas consumption by the BOIc and ICEc. The price of the gas (as shown in Table 10, of the paper) has an incentive of 25% to self-producers who adopt cogeneration devices into their own energy systems. The term $\tau(d)$ was discussed in the section 4.1 of the paper.

Similarly, the operation cost regarding the buildings (Eq. (S2)) comprises also the gas consumption by boilers and cogeneration systems. The difference is that the latter can comprise ICE and MGT.

$$OC_{central} = \sum_{m=1}^{12}\sum_{d=1}^{2}\sum_{h=1}^{24}\Big[gas_{price_BOI}\cdot Fuel_{BOIc}(m,d,h) + gas_{price_ICE} \cdot Fuel_{ICEc}(m,d,h)\Big]\cdot\tau(d) \quad \text{(S1)}$$

$$OC_{building}(B) = \sum_{m=1}^{12}\sum_{d=1}^{2}\sum_{h=1}^{24}\left[gas_{price_BOI}\cdot Fuel_{BOI}(m,d,h) + gas_{price_ICE} \cdot \sum_{c=1}^{component}\Big(Fuel_{ICE}(m,d,h,B) + Fuel_{MGT}(m,d,h,B)\Big)\right]\cdot\tau(d) \quad \text{(S2)}$$

Equations (S3) and (S4) calculate the maintenance costs of the technologies installed in the central unit and in each building, respectively. From the four technologies comprising the superstructure of the central unit, only the BOIc and ICEc were assumed to produce a maintenance cost. Equation (S4) computes the hourly maintenance cost for each building and for each one of the ten technologies (comprising the building superstructure) but the thermal storages (HST and CST), which were assumed as zero-maintenance technologies. Although foreseen in the equation, the maintenance factors for PV and ST were assumed to be zero in this work.

$$mC_{central} = m_{BOIc}\cdot Heat_{BOIc} + m_{ICEc}\cdot Elec_{ICEc} \quad \text{(S3)}$$

$$\begin{aligned} mC_{building}(B) = \sum_{m=1}^{12}\sum_{d=1}^{2}\sum_{h=1}^{24}\Bigg[& m_{BOI}\cdot Heat_{BOI}(m,d,h,B) + m_{CC}\cdot Cool_{CC}(m,d,h,B) \\ & + m_{PV}\cdot Elec_{PV}(m,d,h,B) + m_{ST}\cdot Heat_{ST}(m,d,h,B) + m_{MGT} \\ & \cdot \sum_{c=1}^{component} Elec_{MGT}(m,d,h,c,B) + m_{ICE} \\ & \cdot \sum_{c=1}^{component} Elec_{ICE}(m,d,h,c,B) + m_{ABS} \\ & \cdot \sum_{c=1}^{component} Cool_{ABS}(m,d,h,c,B) + m_{HP} \\ & \cdot \sum_{c=1}^{component} Elec_{HP}(m,d,h,c,B)\Bigg]\cdot\tau(d) \end{aligned} \quad \text{(S4)}$$

Equations (S5) to (S8) show how the annual investment costs were calculated. Equation (S5) calculates the annual investment concerning the technologies in the central unit. The IC_{tech}

values can be found in section 3.1, the capital recovery factor (f_{tech}) can be calculated through Eq. (S6) ($i = 5\%$), and the lifetime of each technology can be found in Table S20.

Table S20. Lifetime of the adopted technologies.

	MGT	ICE	BOI	CC	HP	ABS	ST	PV	HST	CST	DHCN
Lifetime [years]	15	15	10	10	15	15	20	20	20	20	30

The annual investment cost concerning the technologies installed in each building of the EC is calculated through Eq. (S7). As observed, besides the capital recovery factor and the investment cost, the annual cost of the technologies MGT, ICE, ABS, and HP depends also on two important aspects: (i) the existence (X_{tech}) (in the optimal solution) of the technology, and (ii) the factor $IC_{install}(c)$ which tells the models that there is a discount on the installation of the equipment, starting from the second one (Table S21). the remaining technologies depend only on the capital recovery factor and their optimal size.

Table S21. Factor to account for a cost reduction when installing more than one from the same technology.

	Installed technology					
	First	**Second**	**Third**	**Fourth**	**Fifth**	**Sixth**
$\boldsymbol{IC_{install}(c)}$	1.00	0.80	0.75	0.70	0.70	0.70

$$IC_{central} = IC_{ICEc} \cdot f_{ICE} + IC_{BOIc} \cdot f_{BOI} + IC_{STc} \cdot f_{ST} + IC_{HSTc} \cdot f_{HST} \quad \text{(S5)}$$

$$f_{tech} = \frac{i \cdot (1+i)^{lifetime_tech}}{(1+i)^{lifetime_tech} - 1} \quad \text{(S6)}$$

$$
\begin{aligned}
IC_{building}(B) = f_{MGT} \cdot & \sum_{c=1}^{component} \left(X_{MGT}(c,B) \cdot IC_{MGT}(B) \cdot IC_{install}(c)\right) + f_{ICE} \\
& \cdot \sum_{c=1}^{component} \left(X_{ICE}(c,B) \cdot IC_{ICE}(B) \cdot IC_{install}(c)\right) + f_{ABS} \\
& \cdot \sum_{c=1}^{component} \left(X_{ABS}(c,B) \cdot IC_{ABS}(B) \cdot IC_{install}(c)\right) + f_{HP} \\
& \cdot \sum_{c=1}^{component} \left(X_{HP}(c,B) \cdot IC_{HP}(B) \cdot IC_{install}(c)\right) + f_{BOI} \cdot Size_{BOI}(B) \\
& \cdot IC_{BOI} + f_{CC} \cdot Size_{CC}(B) \cdot IC_{CC} + f_{PV} \cdot Size_{PV}(B) \cdot IC_{PV} + f_{ST} \\
& \cdot Size_{ST}(B) \cdot IC_{ST} + f_{HST} \cdot Size_{HST}(B) \cdot IC_{HST} + f_{CST} \cdot Size_{CST}(B) \\
& \cdot IC_{CST}
\end{aligned}
\tag{S7}
$$

Equation (S8) computes the annual investment cost regarding the DHCN pipelines. The equation is composed essentially by two parts: the first one for the pipes connecting the buildings and the second one for the pipe connecting the central unit and the buildings. The two parts are dependent on the length of the pipes and the variable and fixed investment costs. The variable costs are linked to the optimal sizes of the pipes whereas the fixed cost is related to the existence of a given pipeline connection.

$$
\begin{aligned}
IC_{pipes} = \Bigg[& \sum_{k,B \mid k \neq B} \Big[L_{pipe}(k,B) \cdot \left(Size_{pipe_c}(k,B) + Size_{pipe_h}(k,B)\right) \cdot IC_{pipes_v} \\
& + \left(X_{pipe_c}(k,B) + X_{pipe_h}(k,B)\right) \cdot IC_{pipes_f} \Big] + L_{central} \\
& \cdot \left(Size_{pipe_{central}} \cdot IC_{pipescentral_v} + X_{pipe_central} \cdot IC_{pipescentral_f}\right) \Bigg] \\
& \cdot f_{pipes}
\end{aligned}
\tag{S8}
$$

4.2 Models of the adopted technologies

The energy production as well as the boundary of the system are two of the main details described in the models of each technology. The following two subsections describe the models of each technology considered in the superstructure of the EC, for both the buildings and central unit.

4.2.1 Buildings

The superstructure of each building comprises: micro gas turbine (MGT), internal combustion engine (ICE), boiler (BOI), absorption chiller (ABS), compression chiller (CC), heat pump, (HP), photovoltaic panels (PV), solar thermal panels (ST), hot water storage (HST), and chilled water storage (CST). In this section, the model of each one of these technologies is presented. The reader should bear in mind that, from Eq. (S9) to Eq. (S45), the hourly dependency of the variables, represented by *m* (month), *d* (day), and *h* (hour), is replaced by t for simplicity.

Micro gas turbine (MGT)

There are four nominal MGT sizes that can be installed, depending on the building: 30, 65, 100, and 200 kW. The performance data for each nominal size was obtained from manufacture's catalogues and are detailed in section 2. The linearized equations derived from the performance curves of the MGTs are shown in Eq. (S9) and Eq. (S10). They represent, respectively, the heat production ($Heat_{MGT}$) and the fuel consumption ($Fuel_{MGT}$) as function of the produced electricity (E_{MGT}). In this way, the model is able to calculate the exact value of the device's efficiencies (electric or thermal ones) for any partial load level, between the minimum ($MGT_{\min}$) and maximum ($MGT_{\max}$) capacities.

$$Heat_{MGT}(t,c,B) = kh_{MGT}(t,B,1) \cdot E_{MGT}(t,c,B) + kh_{MGT}(t,B,2) \cdot O_{MGT}(t,c,B) \quad \text{(S9)}$$

$$Fuel_{MGT}(t,c,B) = kf_{MGT}(t,B,1) \cdot E_{MGT}(t,c,B) + kf_{MGT}(t,B,2) \cdot O_{MGT}(t,c,B) \quad \text{(S10)}$$

$$MGT_{\min}(t,B) \cdot O_{MGT}(t,c,B) \leq E_{MGT}(t,c,B) \leq MGT_{\max}(t,B) \cdot O_{MGT}(t,c,B) \quad \text{(S11)}$$

$$O_{MGT}(t,c,B) \leq X_{MGT}(c,B) \quad \text{(S12)}$$

$$X_{MGT}(c,B) \leq X_{MGT}(c-1,B) \quad \text{(S13)}$$

The obtainment of the linear coefficients in Eq. (S9) and (S10) (kh_{MGT} and kf_{MGT}) are explained in the section 2. Equation (S11) represents the limits of electricity production and defines whether the electricity production is zero or not, through the operation binary variable O_{MGT}. Equation (S12) tells the model that the technology is able to operate only if it was installed. The installation decision is made through the binary variable X_{MGT}. The model is able to install up to six components of the same technology. Bearing in mind that the model considers lower investment values for installing components starting from the second one on, Eq. (S13) guarantees that the installation of the second component is allowed only if the first one is already installed.

Internal combustion engine (ICE)

Table S2 (of the paper) also presents the nominal ICE sizes according to the building: 50, 70, 140, and 200 kW. The reasoning about Eq. (S14) to Eq. (S18) is analogous to the one of MGT (Eq. (S9) to Eq. (S13)).

$$Heat_{ICE}(t,c,B) = kh_{ICE}(t,B,1) \cdot E_{ICE}(t,c,B) + kh_{ICE}(t,B,2) \cdot O_{ICE}(t,c,B) \quad \text{(S14)}$$

$$Fuel_{ICE}(t,c,B) = kf_{ICE}(t,B,1) \cdot E_{ICE}(t,c,B) + kf_{ICE}(t,B,2) \cdot O_{ICE}(t,c,B) \quad \text{(S15)}$$

$$ICE_{\min}(t,B) \cdot O_{ICE}(t,c,B) \leq E_{ICE}(t,c,B) \leq ICE_{\max}(t,B) \cdot O_{ICE}(t,c,B) \quad \text{(S16)}$$

$$O_{ICE}(t,c,B) \leq X_{ICE}(c,B) \quad \text{(S17)}$$

$$X_{ICE}(c,B) \leq X_{ICE}(c-1,B) \quad \text{(S18)}$$

Boiler (BOI)

The auxiliary boiler produces the required amount of heat ($Heat_{BOI}$) limited to the installed capacity Cap_{BOI}. In this case, there is no variation in the index c since only one boiler is allowed to be installed. What varies is the size of the equipment. Both $Heat_{BOI}$ and Cap_{BOI} are decision variables, which means that the algorithm is free to install (or not) an optimal capacity, according to the objective function under scrutiny.

$$Fuel_{BOI}(t,B) = Heat_{BOI}(t,B)/\eta_{BOI} \quad \text{(S19)}$$

$$Heat_{BOI}(t,B) \leq Cap_{BOI}(B) \quad \text{(S20)}$$

Absorption chiller (ABS)

The ABS nominal sizes, according to each building, are: 35, 70, 105 kW. The hourly cooling production $Cool_{ABS}$ is expressed by Eq. (S21) and is related to the heat consumption $Heat_{ABS}$ through the COP_{ABS}. The cooling production is limited to a minimum and maximum values, as observed on Eq. (S22). The binary variables O_{ABS} and X_{ABS} define the operation and existence (or installation) of an ABS unit, respectively.

Equation (S23) tells the model that the technology is able to operate only if it was installed. In a similar way as for MGT and ICE, Eq. (S24) guarantees that the installation of the second ABS unit is allowed only if the first one is already installed. Another important restriction of the model is to make sure that the ABS can be fed only by heat from solar thermal (ST), MGT, and/or ICE, which is the purpose of Eq. (S25).

$$Heat_{ABS}(t,c,B) \cdot COP_{ABS}(t,B) - Cool_{ABS}(t,c,B) = 0 \quad \text{(S21)}$$

$$ABS_{min}(t,B) \cdot O_{ABS}(t,c,B) \leq Cool_{ABS}(t,c,B) \leq ABS_{max}(t,B) \cdot O_{ABS}(t,c,B) \quad \text{(S22)}$$

$$O_{ABS}(t,c,B) \leq X_{ABS}(c,B) \quad \text{(S23)}$$

$$X_{ABS}(c,B) \leq X_{ABS}(c-1,B) \quad \text{(S24)}$$

$$Heat_{ST}(t,B) - Heat_{HST}(t,B) + \sum_{c=1}^{6}(Heat_{MGT}(t,c,B) + Heat_{ICE}(t,c,B)) - \sum_{c=1}^{6} Heat_{ABS}(t,c,B) \geq 0 \quad \text{(S25)}$$

Compression chiller (CC)

The hourly cooling produced by the CC ($Cool_{CC}$) is associated to the hourly consumed electricity $Elec_{CC}$ through COP_{CC} (Eq. (S26)) and is limited to the installed capacity Cap_{CC} (Eq. (S27)). Analogously to the BOI case, CC has no variation in the index c since only one CC is allowed to be installed. What varies is the size of the equipment. Both $Cool_{CC}$ and Cap_{CC} are decision variables, which means that the algorithm is free to install (or not) an optimal capacity, according to the objective function under analysis.

$$Elec_{CC}(t,B) = Cool_{CC}(t,B)/COP_{CC} \quad \text{(S26)}$$

$$Cool_{CC}(t,B) \leq Cap_{CC}(B) \quad \text{(S27)}$$

Heat pump (HP)

The HP nominal sizes, according to each building, are: 35, 80, 100 kW. The HP can deliver heat or cooling as products by consuming electricity. The heat $Heat_{HP}$ and cooling $Cool_{HP}$ hourly productions are obtained through Eq. (S28) and Eq. (S29), and are related to the electricity consumption via the COP of each operation mode. Equation (S30) expresses the fact that the total electricity consumed by the HP is the summation of the electricity consumed in both operation modes.

The operation in cooling or heat mode is specified through the binary variables O_{HP_c} and O_{HP_h}, while X_{HP} expresses the installation (or not) of the device. Then, for both operation modes, the following equations represent: (i) the electricity consumption limits (Eq. (S31) and Eq. (S32)), (ii) the fact that a technology can operate only if it is installed (Eq. (S33) and Eq. (S34)), (iii) the constraint to tell the model that cooling and heat mode cannot operate at the same time

(Eq. (S35)), and (iv) the allowance to install a second HP only if the first one have already been installed (Eq. (S36)).

$$Heat_{HP}(t,c,B) = COP_{HP_heat}(t,B) \cdot Elec_{HP_h}(t,c,B) \quad \text{(S28)}$$

$$Cool_{HP}(t,c,B) = COP_{HP_cooling}(t,B) \cdot Elec_{HP_c}(t,c,B) \quad \text{(S29)}$$

$$Elec_{HP}(t,c,B) = Elec_{HP_h}(t,c,B) + Elec_{HP_c}(t,c,B) \quad \text{(S30)}$$

$$HP_{\min_h}(t,B) \cdot O_{HP_h}(t,c,B) \leq Elec_{HP_h}(t,c,B) \leq HP_{\max_h}(t,B) \cdot O_{HP_h}(t,c,B) \quad \text{(S31)}$$

$$HP_{\min_c}(t,B) \cdot O_{HP_c}(t,c,B) \leq Elec_{HP_c}(t,c,B) \leq HP_{\max_c}(t,B) \cdot O_{HP_c}(t,c,B) \quad \text{(S32)}$$

$$O_{HP_h}(t,c,B) \leq X_{HP}(c,B) \quad \text{(S33)}$$

$$O_{HP_c}(t,c,B) \leq X_{HP}(c,B) \quad \text{(S34)}$$

$$O_{HP_h}(t,c,B) + O_{HP_c}(t,c,B) \leq 1 \quad \text{(S35)}$$

$$X_{HP}(c,B) \leq X_{HP}(c-1,B) \quad \text{(S36)}$$

Solar technologies (PV and ST)

The solar technologies comprise photovoltaic panels (PV) and flat-plate solar thermal panels (ST). The hourly PV electricity production $Elec_{PV}(t, B)$ is expressed by Eq. (S37) and depends on two terms: (i) $k_{PV}(t)$ which is the hourly PV electricity production per m^2 (kW/ m^2) obtained from local solar irradiation data, and (ii) $Cap_{PV}(B)$ which is the installed PV capacity (in m^2) of a given building and a decision variable. Then, the hourly ST heat production $Heat_{ST}(t, B)$ is calculated through Eq. (S38) and also depends on two terms: (i) $k_{ST}(t)$ which is the hourly ST heat production per m^2 (kW/m^2) obtained from local solar irradiation data, and (ii) $Cap_{ST}(B)$ which is the installed ST capacity (in m^2) of a given building and also a decision variable.

$$Elec_{PV}(t,B) = k_{PV}(t) \cdot Cap_{PV}(B) \quad \text{(S37)}$$

$$Heat_{ST}(t,B) = k_{ST}(t) \cdot Cap_{ST}(B) \quad \text{(S38)}$$

$$Cap_{PV}(B) + Cap_{ST}(B) \leq Avail_area_{rooftop}(B) \quad \text{(S39)}$$

Equation (S39) restricts the installation of the solar technologies to a maximum available rooftop area. Besides, this equation gives the model the task to decide which solar technology is more advantageous to install, according to the objective function under analysis.

Hot water storage (HST)

The hourly heat flow in or out of the HST ($Heat_{HST_in_out}$) is given by Eq. (S40). When the heat stored at a given hour h ($HST_{stored}(t, B)$) is greater than the heat stored at the previous hour (minus heat losses) ($heat_{loss_HST} \cdot HST_{stored}(t-1, B)$), it means that the hourly heat flow variable is positive and the HST is being charged. Conversely, if $heat_{loss_HST} \cdot HST_{stored}(t-1, B) > HST_{stored}(t, B)$, it means that the hourly heat flow variable is negative and the HST is being discharged. The HST model is not based on typical days. It is modelled for the whole year. For that reason, the HST model demanded more detailed equations to express not only transitions between hours, but also the transitions between days, weeks, and months.

Equation (S41) limits the allowed hourly amount of heat that can be stored in the HST. The variable $Size_{HST}(B)$, in kWh, is the size limit and, at the same time, is a decision variable constrained to a maximum allowed HST capacity for each building (Eq. (S42)).

$$Heat_{HST_in_out}(t, B) = HST_{stored}(t, B) - heat_{loss_HST} \cdot HST_{stored}(t-1, B) \quad \text{(S40)}$$

$$HST_{stored}(t, B) \leq Size_{HST}(B) \quad \text{(S41)}$$

$$Size_{HST}(B) \leq Cap_HST_{max} \quad \text{(S42)}$$

Chilled water storage (CST)

The logic of the CST model follows a similar procedure as of HST model.

$$Cool_{CST_in_out}(t, B) = CST_{stored}(t, B) - cool_{loss_CST} \cdot CST_{stored}(t-1, B) \quad \text{(S43)}$$

$$CST_{stored}(t, B) \leq Size_{CST}(B) \quad \text{(S44)}$$

$$Size_{CST}(B) \leq Cap_CST_{max} \quad \text{(S45)}$$

4.2.2 Central unit

The superstructure of the central unit comprises internal combustion engine (ICEc), boiler (BOIc), solar thermal panels (STc), and hot water storage (HSTc). In this section, the model of each one of these technologies is presented. From Eq. (S46) to Eq. (S57), the hourly dependency of the variables, represented by *m* (month), *d* (day), and *h* (hour), is replaced by t for simplicity.

Internal combustion engine (ICEc)

The ICEc electricity ($Elec_{ICEc}$) and heat ($Heat_{ICEc}$) products are expressed through Eq. (S46) and Eq. (S47). Both heat and fuel are written as functions of the produced electricity since the latter is the decision variable. The linear coefficients are $kh_{ICEc} = 1.175$ and $kf_{ICEc} = 2.646$, which means efficiencies of 44.4% and 37.8% for heat and electricity products, respectively.

Then, Eq. (S48) sets the minimum and maximum limits for $Elec_{ICEc}$, where $Elec_{ICEc_min} = 0.2$, and Eq. (S49) establishes the boundaries for the ICEc size. The $Size_{ICEc}$ is also a decision variable.

$$Heat_{ICEc}(t) = kh_{ICEc} \cdot Elec_{ICEc}(t) \quad \text{(S46)}$$

$$Fuel_{ICEc}(t) = kf_{ICEc} \cdot Elec_{ICEc}(t) \quad \text{(S47)}$$

$$Elec_{\text{ICEc_min}} \cdot Size_{ICEc} \leq Elec_{ICEc}(t) \leq Size_{ICEc} \quad \text{(S48)}$$

$$Size_{\text{ICEc_min}} \cdot X_{ICEc} \leq Size_{ICEc} \leq Size_{\text{ICEc_max}} \cdot X_{ICEc} \quad \text{(S49)}$$

Boiler (BOIc)

The hourly heat ($Heat_{BOIc}$) produced by the central unit boiler is calculated through Eq. (S50), where η_{BOIc} is the boiler efficiency and $Fuel_{BOIc}$ is the hourly amount of consumed fuel. In a different way as for the boiler of the buildings' superstructure, a minimum amount of produced heat should be set for the BOIc. Moreover, in order to introduce a linear relation between two decision variables ($Heat_{BOIc}(t)$ and $Size_{BOIc}$), an auxiliary variable $\varphi_{BOIc}(t)$ should be introduced. Therefore, Eq. (S51) to Eq. (S53) present a set of additional constraints in order to (i) allow the specification of a minimum value for $Heat_{BOIc}(t)$, and (ii) provide a linear relation between the hourly produced heat and the boiler size. $Fuel_{BOIc_min}$ is set to 10%, while $O_{BOIc}(t)$ and X_{BOIc} are binary variables to specify operation and existence status, respectively.

$$Fuel_{BOIc}(t) = Heat_{BOIc}(t)/\eta_{BOIc} \quad \text{(S50)}$$

$$Fuel_{BOIc_min} \cdot \varphi_{BOIc}(t) \leq Heat_{BOIc}(t) \leq \varphi_{BOIc}(t) \quad \text{(S51)}$$

$$Size_{BOIc} + Size_{BOIc_max} \cdot (O_{BOIc}(t) - 1) \leq \varphi_{BOIc}(t) \leq Size_{BOIc} \quad \text{(S52)}$$

$$Size_{BOIc_min} + X_{BOIc} \leq Size_{BOIc} \leq Size_{BOIc_max} + X_{BOIc} \quad \text{(S53)}$$

Solar thermal panels (STc)

The hourly heat produced $Heat_{STc}$ by the STc installed in the central unit (Eq. (S54)) is calculated in a similar way as the one for ST on buildings, where $k_{ST}(t)$ is the hourly STc heat production per m^2 (kW/m^2), obtained from local solar irradiation data, and Cap_{STc} is the installed capacity in m^2.

$$Heat_{STc}(t) = k_{ST}(t) \cdot Cap_{STc} \quad \text{(S54)}$$

Hot water storage (HSTc)

The central unit HSTc is modelled (Eq. (55) to Eq. (57)) in a similar way as for the buildings HST. Time dependency is the same. The only difference is that HSTc is not building dependent.

$$Heat_{HSTc_in_out}(t) = HSTc_{stored}(t) - heat_{loss_HSTc} \cdot HSTc_{stored}(t-1) \quad \text{(S55)}$$

$$HSTc_{stored}(t) \leq Size_{HSTc} \quad \text{(S56)}$$

$$Size_{HSTc} \leq Cap_HSTc_{max} \quad \text{(S57)}$$

5. Results (complement)

5.1 Optimal economic solution: illustration of the polygeneration systems for each building

This section is intended to support the section 5.2.1 of the paper. For the sake of briefness, only the figures regarding the optimal structures of buildings 2 and 7 were presented there. Therefore, the reader will find here the figures regarding the other missing buildings. The discussions related to each figure can be found in the section 5.2.1 of the paper.

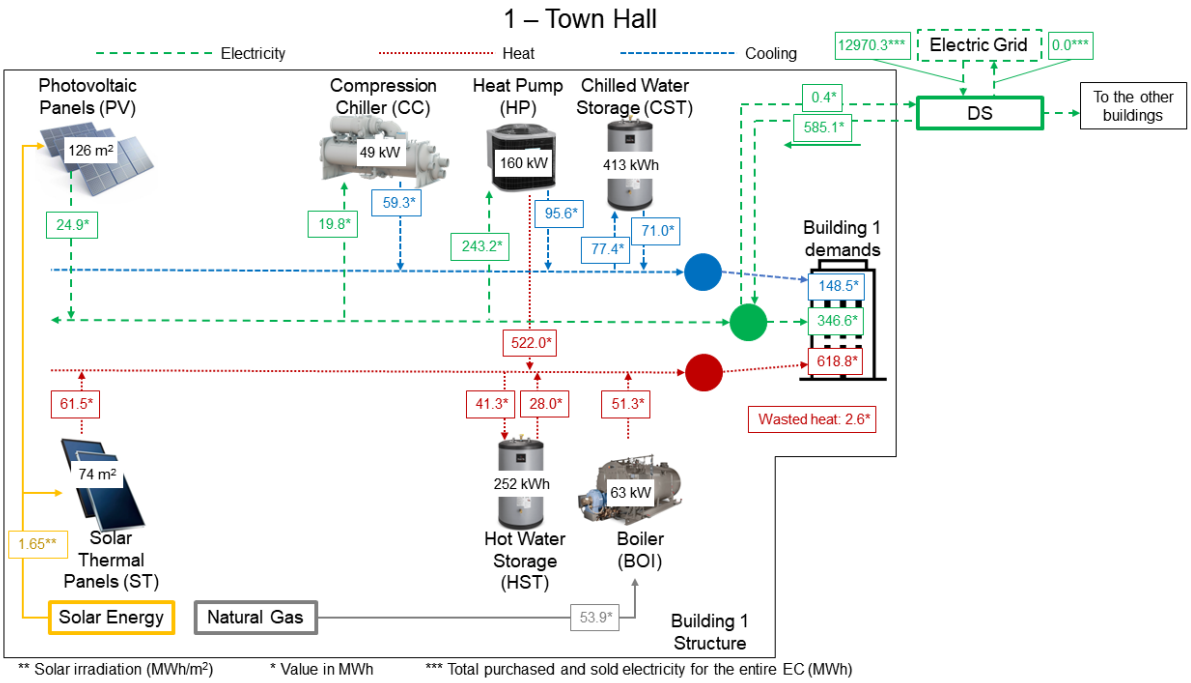


Figure S32. Installed capacities and annual energy flows for building 1 (Town Hall).

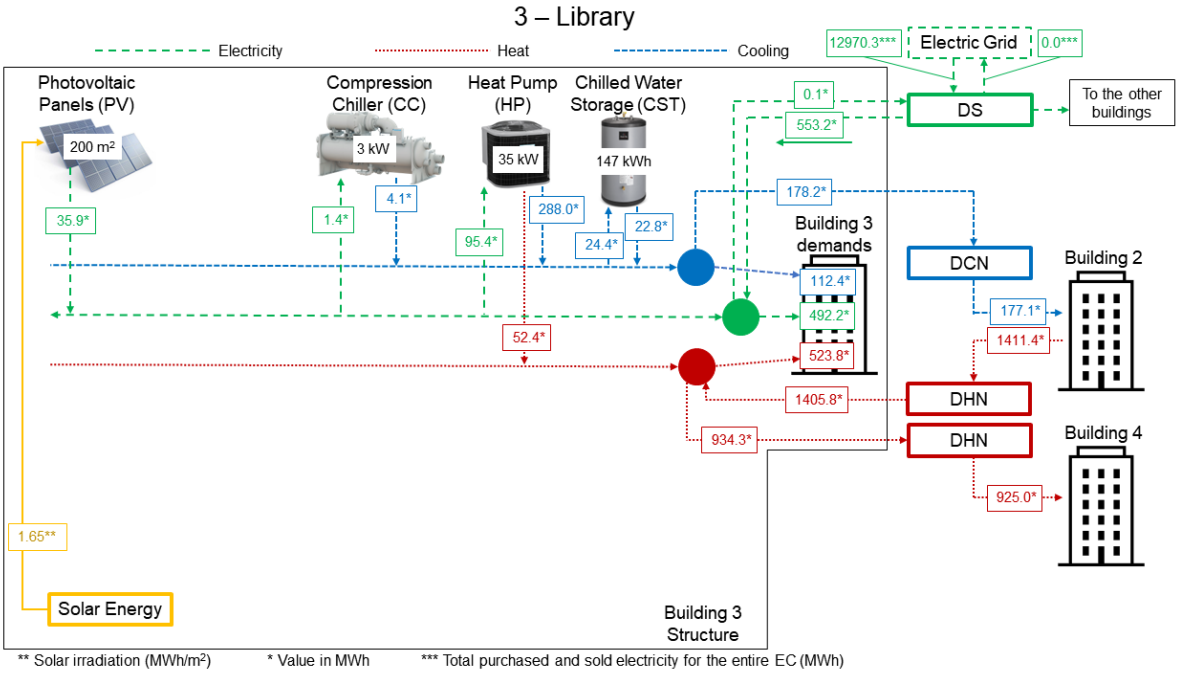


Figure S33. Installed capacities, annual energy flows, and DHCN connections for building 3 (Library).

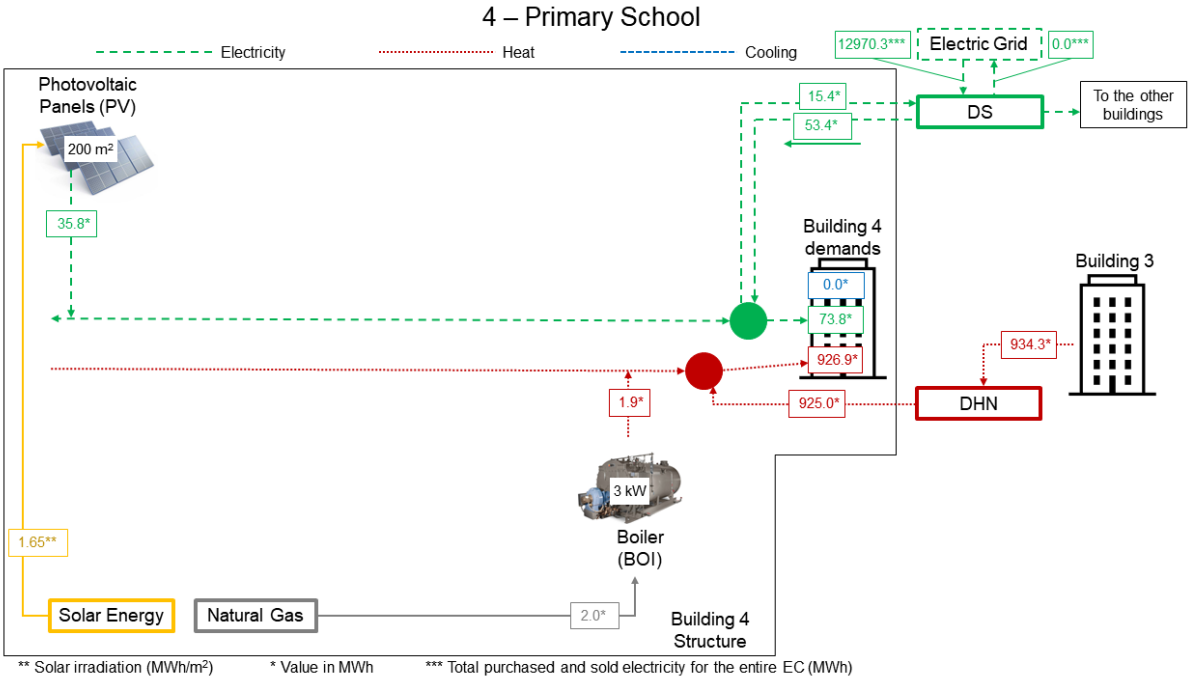


Figure S34. Installed capacities, annual energy flows, and DHN connection for building 4 (Primary school).

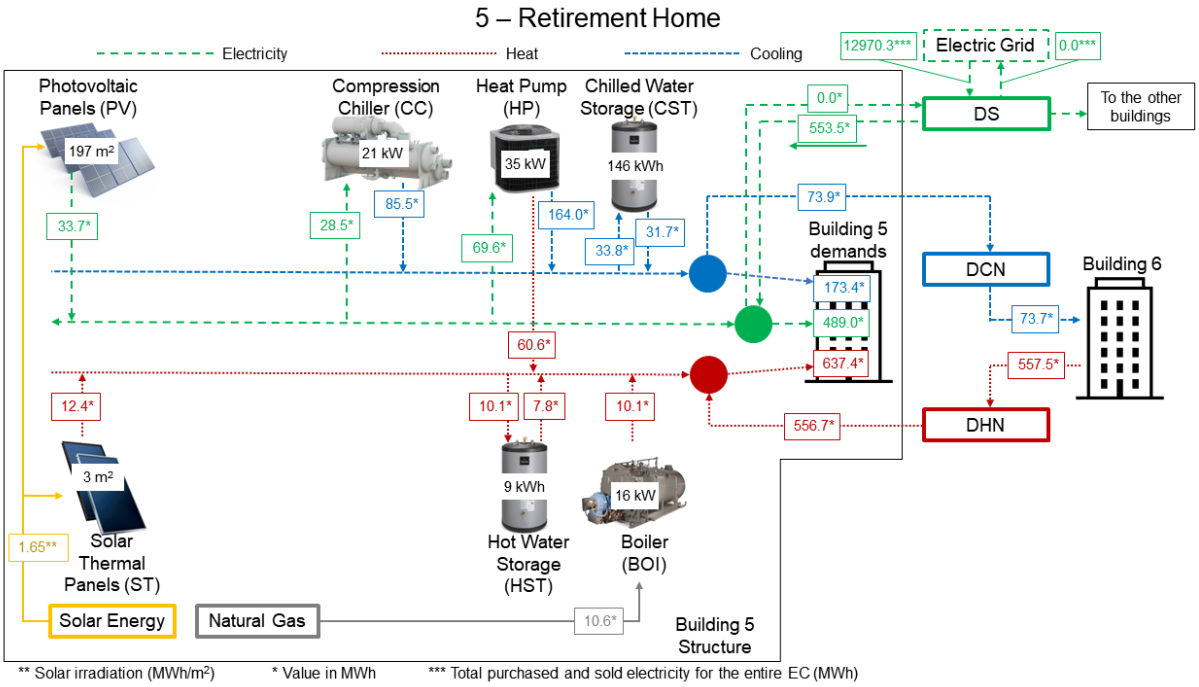


Figure S35. Installed capacities, annual energy flows, and DHCN connection for building 5 (Retirement home).

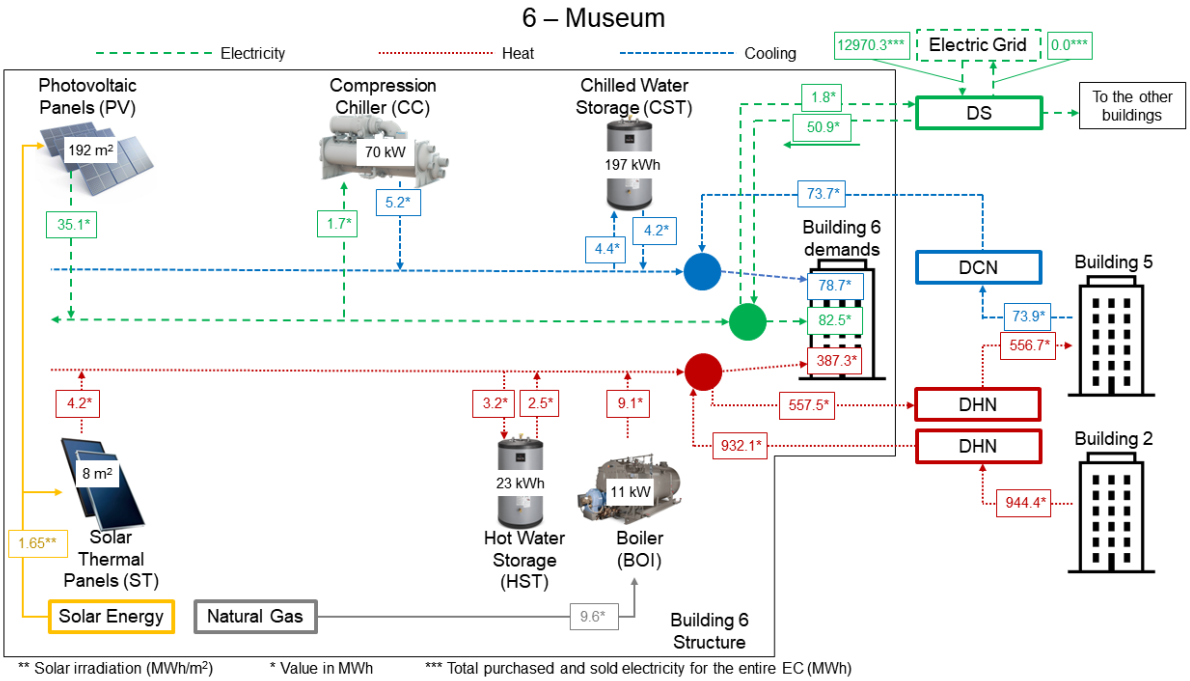


Figure S36. Installed capacities, annual energy flows, and DHCN connection for building 6 (Museum).

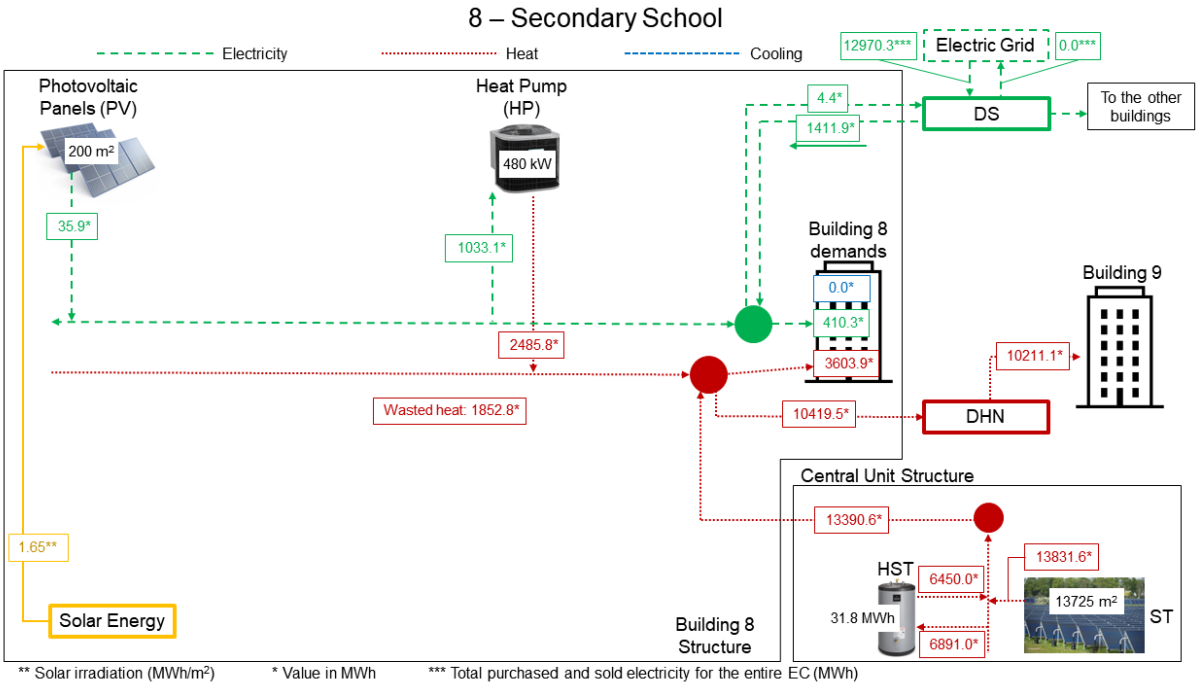


Figure S37. Installed capacities, annual energy flows, and DHN connection for building 8 (Secondary school).

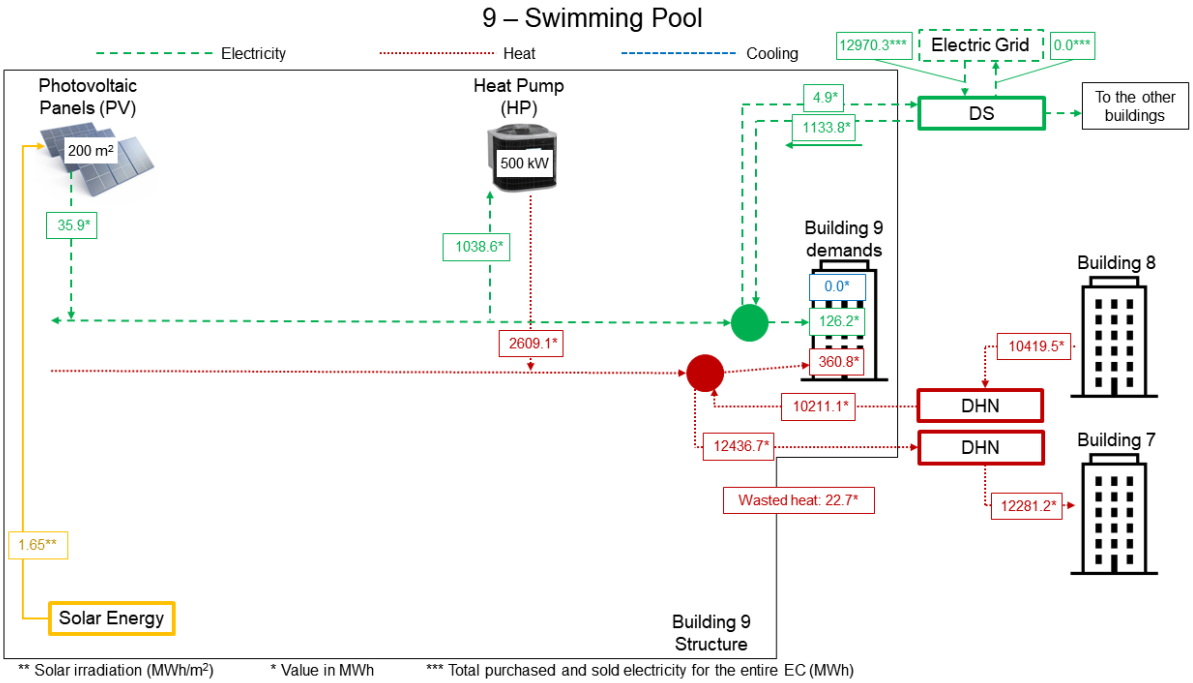


Figure S38. Installed capacities, annual energy flows, and DHN connection for building 9 (Swimming pool).

References

1. Buoro, D. Development of an Environmental and Economic Optimization Model for Distributed Generation Energy Systems. PhD Thesis, University of Udine, 2013.
2. Bellina, R. Progetto Ottimo Di Un Sistema Integrato Con Impianto Trigenerativo e Rete Di Teleriscaldamento per Il Comune Di Tolmezzo, University of Udine, 2012.
3. Viessmann *VITOBLOC 200: Gruppo Di Cogenerazione - Elettricità e Calore Da Gas Metano*; 2020;
4. Capstone *Capstone Microturbine Technical Reference*; Los Angeles, CA, USA, 2009;
5. Yazaki *Water Fired Absorption Chillers WFC Series*; 2018;
6. Daikin *Chillers: Commercial and Technical Data*; 2013;
7. NREL System Advisor Model 2023.
8. ARERA ARERA - Delibera181/2006. Aggiornamento Delle Fasce Orarie Con Decorrenza 1 Gennaio 2007.
9. GME GME - Gestore Mercati Energetici. Prezzo Medio per Fasce.
10. ARERA ARERA - Autorità Di Regolazione per Energia, Reti e Ambiente - Dati Statistici.
11. GSE GSE - Electricity Selling Price. Ritiro Dedicato - Archivio Prezzi Medi Mensili 2008 - 2022.
12. GSE GSE - Gestore Dei Servizi Energetici. Ritiro Dedicato.