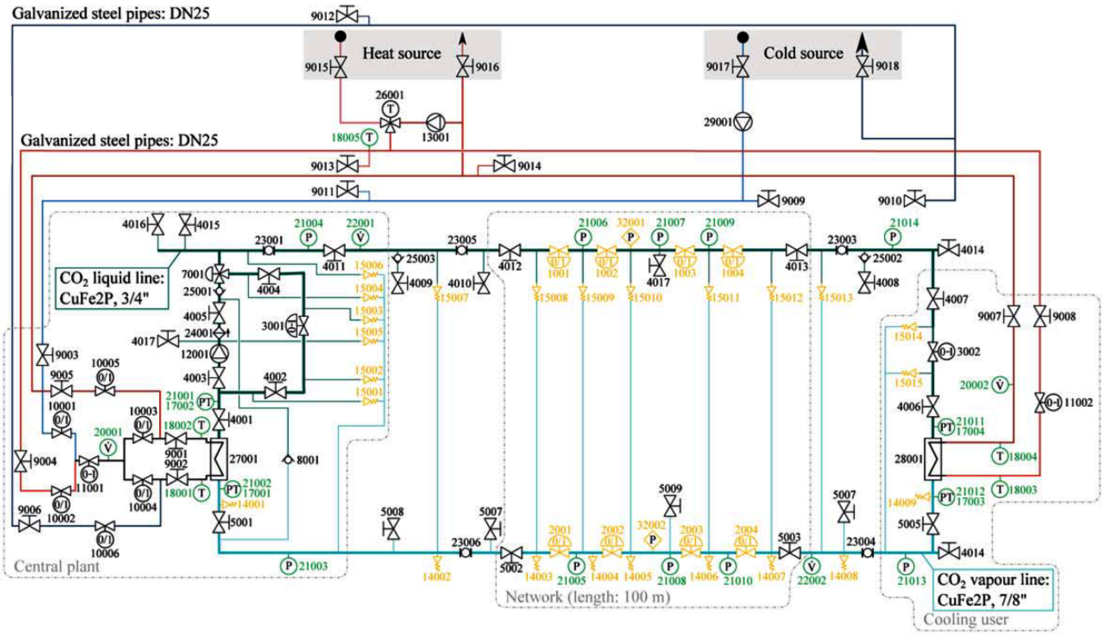
$CO_2$-based System in NEST

# FEASIBILITY STUDY OF A $CO_2$-BASED SYSTEM IN NEST

## TECHNICAL REPORT

March 2017



$CO_2$ heat distribution system, S.Henchoz, LENI-EPFL, 2016.

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NEST - EMPA

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# Feasibility study of a $CO_2$-based system in NEST

Technical Report
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# Nomenclature

| | |
|---|---|
| 4GDH | $4^{th}$ Generation District Heating |
| $CO_2$/R744 | Carbon Dioxyde |
| COP | Coefficient of Performance |
| DH | District Heating |
| DHC | District Heating and Cooling |
| DHW | Domestic hot water |
| DN | Nominal Diameter |
| F | Flow, flow meter |
| HP | Heat Pump |
| HT | High temperature water network (7–28/2–18°C) |
| HX | Heat Exchanger |
| LT | Low temperature water network (60–90/45°C) |
| MPC | Model Predictive Control |
| MT | Medium temperature water network (35–38/28°C) |
| P | Pressure |
| P2G | Power to Gas |
| PED | Pressure Equipment Directive 2014/68/EU |
| PEM | Proton exchange membrane fuel cell |
| PS | Maximum allowable Service Pressure |
| PT | Pressure and temperature sensors |
| PV | Photovoltaic system |
| R1234yf | 2,3,3,3-Tetrafluoropropene refrigerant |
| SFW | Solar Fitness and Wellness |
| SN | Swiss Norms |
| T | Temperature |
| V | Volume |

| | |
|---|---|
| $c$ | Space cooling |
| $el$ | Electricity |
| $h$ | Space heating |
| $A_e$ | Energy floor area |
| $A_u$ | Useful floor area |
| $P_c$ | Cooling power |
| $P_h$ | Heating power |
| $P_{dhw}$ | Domestic hot water power |
| $P_{h+dhw}$ | Heating and domestic hot water power |

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# 1 Introduction

The NEST[1] building laboratory of Empa and Eawag is a modular research and innovation demonstrator where new technologies, materials and systems are tested, researched, honed and validated in realistic conditions.
In the NEST concept, only the supporting structure is permanent and all the habitable units are interchangeable. Moreover, the site is hosting an energy research and technology transfer platform (ehub[2]) aiming at optimizing energy management at district level and a demonstrator for future mobility working without fossil energy (move[3]).
Therefore, the NEST research platform seems to be an appropriate place for the implementation of a demonstrator of advanced $4^{th}$ Generation District Heating and Cooling systems (4G-DHC).

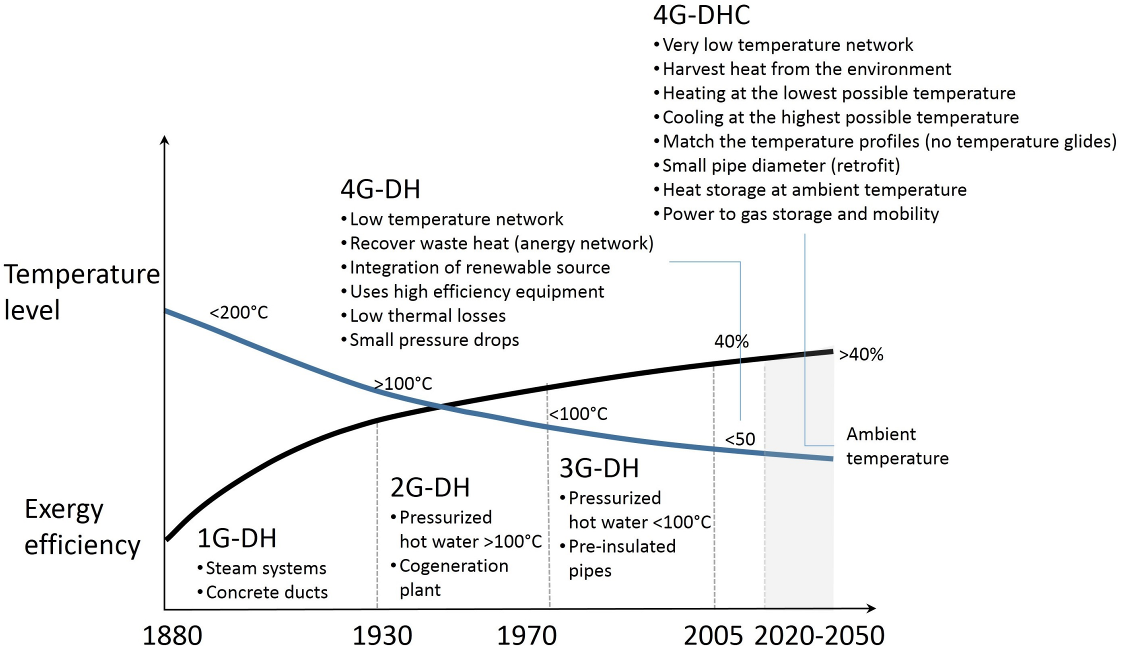

Figure 1: Evolution toward advanced 4G-DHC concepts.

This study demonstrates the feasibility of a $CO_2$-based district energy network in NEST. The report includes a concise project plan (§9, p.23) and budget positions for the concept, planning, installation and operation phase (§8, p.29).

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[1] Empa-Eawag NEST *https://www.empa.ch/web/nest*

[2] Empa EHUB*https://www.empa.ch/web/energy-hub*

[3] Empa MOVE*https://www.empa.ch/web/move*

# 2 Grounds and objectives for a $CO_2$ system in NEST

## 2.1 Motivations

A growing part of the population worldwide will live in cities. Due to the difference of investments between building owners, the level of renovation of buildings is often very diverse, resulting in energy and temperature levels that tend to differ within a given part of city. Moreover, cooling loads tend to increase in central city districts with a large share of shops, offices and data centers. District Heating and Cooling networks (DHC) are therefore growing in already crowded city undergrounds (Figure 2).

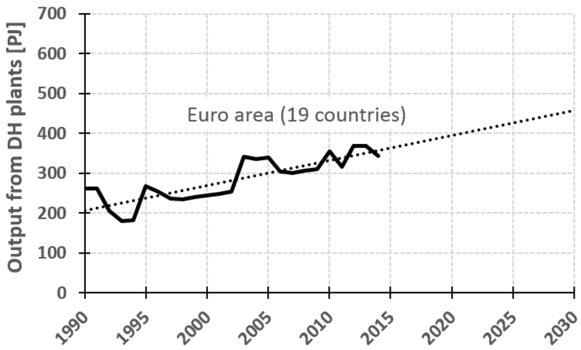

Figure 2: Trend of growth of district heating in EU-19 countries [5]

In line with the design of future 100% renewable energy systems and autonomous cities [19], advanced concepts of district heating and cooling (DHC) systems have recently been proposed [10, 12]. These concepts are built around a "‘smart thermal grid"’ connecting buildings, centralised plants and distributed heating and cooling producing units, including individual contributions from the connected buildings. To fulfill their role in the future renewable energy systems, advanced DHC concepts have to meet the following challenges:

1. supply space heating (SH), cooling (SC) and domestic hot water (DHW) at the appropriate temperature level;
2. distribute heat with low grid losses and low pressure drops;
3. recover waste heat;
4. recycle heat from low-temperature sources and harvest renewable heat sources from the environment, such as solar and geothermal heat;
5. integrate high efficiency equipment (compressors, expanders, pumps);
6. implement heat and power to gas storage at ambient temperature;
7. implement model predictive control (MPC) strategies;
8. integrate multi-energy systems (heat, electricity, gas, mobility);
9. realize a cost effective transition from existing to future energy-autonomous systems.

To face the temperature heterogeneity of building requirements, a concept of very low temperature (DHC) systems has been proposed [20, 9, 6]. The transfer fluid acts as cold network for cooling purposes and supplies evaporator heat to decentralized heat pumps heating the different buildings. Individual heat pumps have the advantage of better efficiency since they supply just the temperature level needs of the individual buildings and consist of a 2 pipe rather than a 4 pipe system (Figure 3).

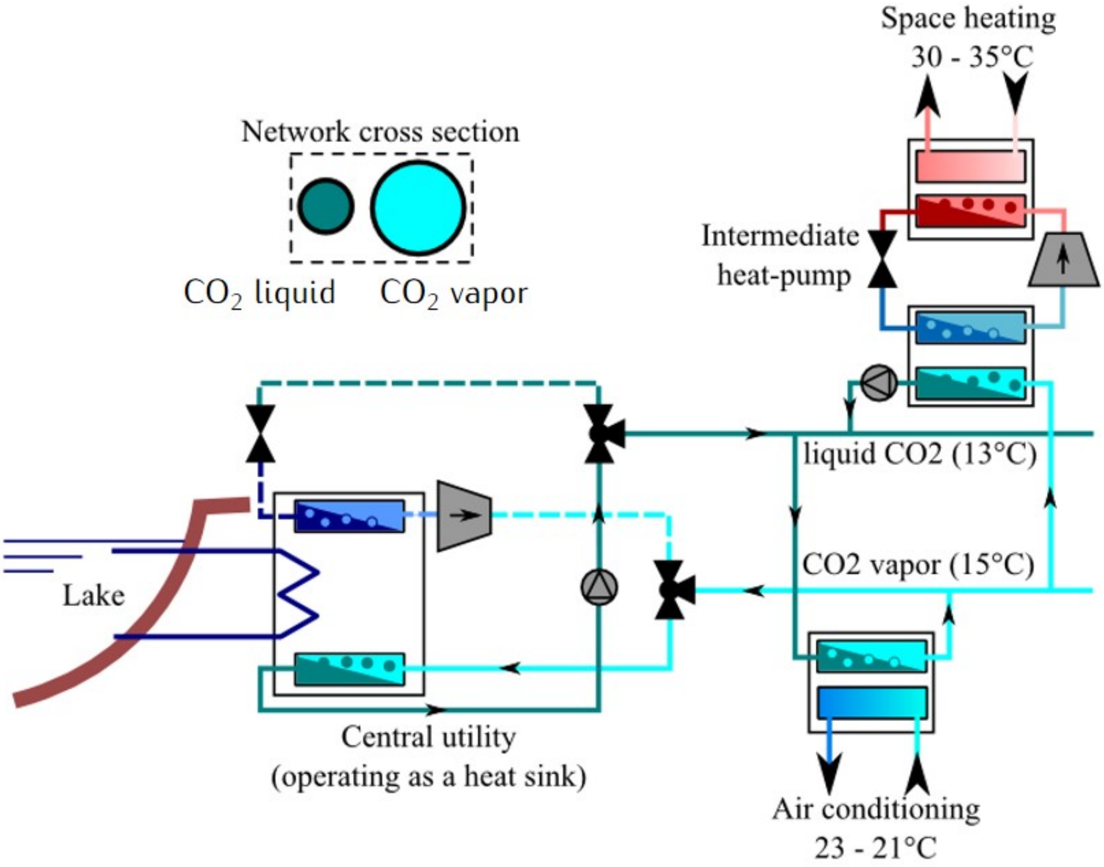

Figure 3: Flowheet of a typical $CO_2$ district heating and cooling network [9, 20].

Such compact district energy networks, in a temperature range of 10 to 16°C, have a great potential for energy savings, by providing a heat source for decentralized heating heat pumps, a cold source for air-conditioning, and a heat sink for refrigeration or cogeneration units.

The energy balance of the network is done by a central plant equipped with a heating heat pump for winter operation and a heat dissipater for summer operation. They typically facilitate the synergy between users and allow the concept of a city without chimneys or cooling towers in the various buildings. One such concept is based on using the latent heat of the transfer fluid ($CO_2$), with one saturated $CO_2$ vapor pipe and one saturated $CO_2$ liquid pipe, in which the flow is bidirectional in the function of the predominance of the heating or cooling demands.

## 2.2 State of the Art

In Switzerland, 373 $CO_2$ refrigeration units have been installed from 2002 to 2013 and since 2010, $CO_2$-only refrigeration systems have been the standard in all new and retrofitted stores[14]. In a SPAR supermarket in Schüpfen[1] (Bern), a fully integrated system allows to recover the heat from the refrigeration process and transports it around the entire store to cover the full annual heating requirements.
In Schlachtbetrieb Zürich[2], the largest $CO_2$ heat pump system in Switzerland (800 $kW_{th}$) is used to produce hot water at 90°C for the slaughterhouse, based on waste heat from refrigeration systems.
These installations circulate evaporating $CO_2$ at high pressure (20-40 bar) inside fridges and freezers out of which customers are taking food. So far, to the best knowledge of the author, no major accident has been reported.

The working principles of the $CO_2$ district energy network of Figure 3 has been demonstrated in 2015 using a modular lab scale experimental facility designed at EPFL-Lausanne [9]. The test bench (Figure 4) is currently hosted at SIG[3] in Geneva and it comprises:

- a central plant working in cooling and heating mode;
- a network with 100m of pipes packed into a volume of $16m^3$;
- a free cooling user at the other end of the network.

An important part of the tests was dedicated to assess the dynamic behaviour of thd $CO_2$ network, to determine the reliability of the automatic control system, and to verify the dynamic stability and reliability of the refrigerant based network.
In spite of the relatively high pressures required by the $CO_2$ network, the experiments at reduced scale did not show any major pressure surge concerns: even if hydro-acoustic phenomena of liquid hammer type can occur in a $CO_2$ based DHC, the magnitude of the phenomenon should not raise special difficulties [9, 6].

## 2.3 Merits and objectives of a $CO_2$ system in NEST

The $CO_2$ system of Figure 3, p.9 is believed to perform better than the conventional water network [11]. It allows to recover internally the residual heat from space cooling using the heat pumps for space heating and hot water production with a COP of 9. Combining the $CO_2$ network, solar panels, electrical and thermal storage with model predictive control (MPC) [15, 18] allows to implement a residential energy-autonomous house with $4m^2$ of PV per capita.

Implementing a $CO_2$ system demonstrator in NEST would mean making a step towards the development of larger scale urban $C0_2$ district networks. It will push the $CO_2$ network concept tested inside the Geneva laboratory, at the demonstrator level.
The objectives of a demonstrator in NEST would be to:

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[1] SPAR supermarket in Schüpfen - $CO_2$OLtec®
[2] Slaughterhouse of Zurich - $thermeco_2$
[3] Services Industriels de Genève *http://www.sig-ge.ch/en*

Figure 4: Modular lab scale experimental facility developed at EPFL and hosted in SIG[1]-Geneva (source: LENI-EPFL, 2011-2015).

- demonstrate the deployment of vertical $CO_2$ networks on the different units of the NEST building;
- demonstrate the combined production of heating and cooling services by integrating heat recovery heat exchangers;
- demonstrate the integration of a decentralised heat pumps for unit heating;
- investigate control strategies for the $CO_2$ network management;
- investigate the integration of a $CO_2$ network for the high temperature heat supply of the unit Solar Fitness and Welness (SFW);
- investigate the integration of a decentralized heat pump for producing hot water.

Moreover, the project will contribute to develop a technical knowledge in mounting techniques in a domain where standards equipments are not yet on the market. Finally, the design of the $CO_2$ system should contribute to the development of norms and standards for the sizing procedures of $CO_2$ urban systems.

## 2.4 Research strategy

The synergies between the existing experimental facilities in Geneva and a future demonstrator in NEST are given in Table 2. The table clearly shows the complementarity and mutual benefit among the projects in terms of objectives, design and operation of equipments.

Table 2: Complementary research fields between laboratory facility and real scale $CO_2$ system demonstrator in NEST.

| **Theme** | **Topics** | **Demonstrator (EMPA NEST/EPFL)** | **Laboratory test bench (HES-SO/SIG-Geneva)** |
|---|---|---|---|
| **Design** | Topology | Vertical | Horizontal |
| | Conception | Robust | Lightweight / Experimental |
| | Modularity | Building space and services constraints | No space or fonctionnal constraint |
| | Assembly techniques | Leading to future industry standards | Plant design standards |
| **Operation** | Working load | Steady state | Steady state and transient |
| | Operation mode | Safe Regular operation | Extrem / Outside regular operation conditions |
| | Operation time | Continuous operation | Discontinus (per demand) operation |
| **Equipments** | Grid coonnected devices | Regular user demand | Simulated demand |
| | Central plant | Regular operating conditions | Simulated operating conditions |
| **Objectives** | Intended purpose | Deployment in building | Deployment in district and cities |
| | Proof of concept | Combination of proved technologies | Test of new technologies |
| | Performances | Long term real condition test | Lab test (specific conditions) |

# 3 Methodology

In a first phase, the available NEST unit geometrical and energy data are presented. In order to identify the most appropriate configuration for a $CO_2$-based demonstrator in NEST, the monthly thermal energy/temperature requirements and sizing power of the planned NEST units are first estimated. This evaluation relies on monthly simulation reports, or on the annual energy from the technical and architectural concept plan. The resulting values are applied to forecast the overall energy demand when all the NEST platforms are occupied.

The $CO_2$-distribution network lines are designed according to the nominal power and location of the NEST units. The energy consumption, operating mode and size of the connected equipments are obtained by simulating the $CO_2$ system using process integration techniques[13] to minimise the annual operating cost

For the deployment of a $CO_2$ system in NEST, a step by step scenario including basic and advanced configurations is given together with the budget positions for the concept. The basic scenario includes at least a central plant, a $CO_2$ distribution line through the upper floors and a decentralized heating and cooling system. The performance of the integrated system is estimated using energy integration techniques and a thermodynamic model for the network lines, heat pumps and heat exchangers.

Finally, the investment, operating and maintenance cost allocation are estimated based on the previous results.

# 4 Space allocation of the NEST units

## 4.1 Floor area

The useful floor area ($A_u$) and the energy floor Area ($A_e$, as defined by the standard SIA 380/1 [1]) of the planned and future NEST units are reported in Table 3. As shown in Figure 5, the units are defined by planning phase (planned/existing versus future platforms, see Figure 6), floor level (1-3) and orientation (North-South) corresponding to the two technical galleries in the NEST-Core building.

For units with unknown ratio of construction ($A_e/A_u$-1), a fraction of 20% is applied by default. The detailed list of room utilisation according to SIA2024[17] are given in Annex B, p.35. The useful area is used later in §5 to obtain a preliminary estimation of the nominal power required according to SIA standard 2024 [17].

Table 3: Planned and future units area on the NEST platforms.

| Unit | Level | Orientation | Au | Ae |
|---|---|---|---|---|
| Meet2Create | 1 | South | 291 m$^2$ | 350 m$^2$ |
| Vision Wood | 2 | South | 119 m$^2$ | 152 m$^2$ |
| SFW | 3 | North | 266 m$^2$ | 275 m$^2$ |
| Hilo | 3 | South | 141 m$^2$ | 180 m$^2$ |
| Urban Minning | 2 | North | 162 m$^2$ | 194 m$^2$ |
| SolAce | 2 | North | 79 m$^2$ | 94 m$^2$ |
| **Total planned platforms**<br>(Construction floor ratio) | | | **1'058 m$^2$** | **1'244 m$^2$**<br>(17.6%) |
| Future platforms North | 1-3 | North | 524 m$^2$ | 616 m$^2$ |
| Future platforms South | 3 | South | 116 m$^2$ | 136 m$^2$ |
| **Total Future platforms** | | | **640 m$^2$** | **753 m$^2$** |
| **Total NEST units** | | | **1'698 m$^2$** | **1'997 m$^2$** |

The total energy area of the planned units is 1'244m$^2$, with a construction floor ratio of 17.6%. This allows to estimate the energy floor area of the future units (753m$^2$), based on the their useful area (640m$^2$).

Figure 5: Planned and future units of the NEST platforms with "‘North"’ and "‘South"’ technical galleries in the middle (black) – Source: Empa.

| Date | Unit | 2016 | 2017 | 2018 |
|---|---|---|---|---|
| January 1, 2016 | NEST Core | 🟩 | 🟩 | 🟩 |
| May 1, 2016 | Meet2Create | 🟩 | 🟩 | 🟩 |
| May 1, 2016 | Vision Wood | 🟩 | 🟩 | 🟩 |
| December 1, 2016 | Solares Fitness & Wellness (SFW) | 🟩 | 🟩 | 🟩 |
| October 1, 2017 | HiLo |  | 🟩 | 🟩 |
| December 1, 2017 | Urban Mining |  | 🟩 | 🟩 |
| December 1, 2017 | SolAce |  | 🟩 | 🟩 |
| December 1, 2017 | AAL |  | 🟩 | 🟩 |
| January 1, 2018 | Digitale Fabrikation |  |  | 🟩 |

Figure 6: NEST units planning

## 4.2 Conclusion

With 1'244 $m^2$, the existing/planned NEST unit represents 62% of the floor energy area available on the NEST platforms. This constitutes a representative basis for the characterisation of the future units as well, providing a baseline for the design of the $CO_2$ system in NEST.
In the existing/planned NEST units, meeting rooms are occupying almost 1/3 of the space, offices 1/5 and sleeping rooms 1/10 (Figure 7).

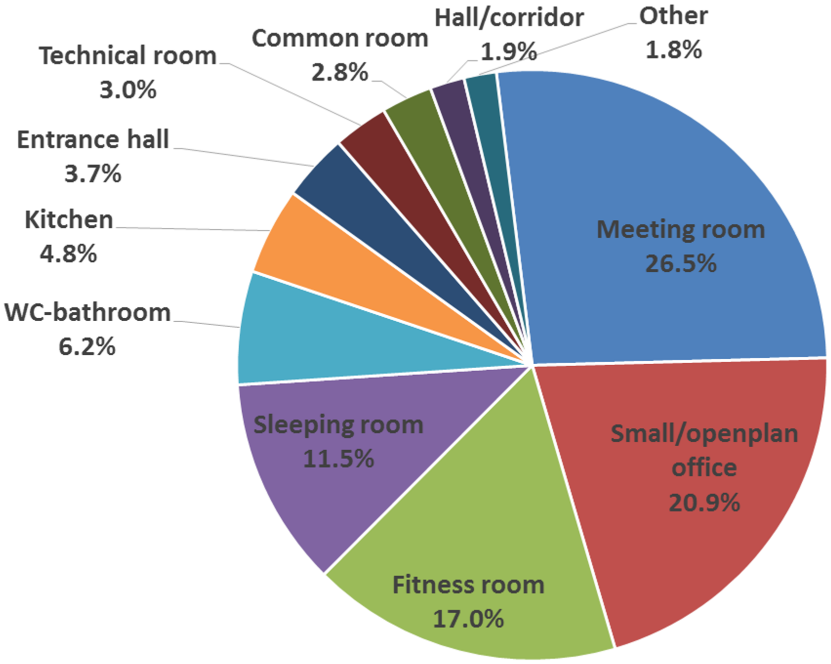

Figure 7: Space allocation of planned/existing unit in NEST

# 5 Energy requirements in NEST

The annual energy demand of NEST units, obtained from monthly simulation reports or from the technical and architectural concept plan are visible in Figure 8.

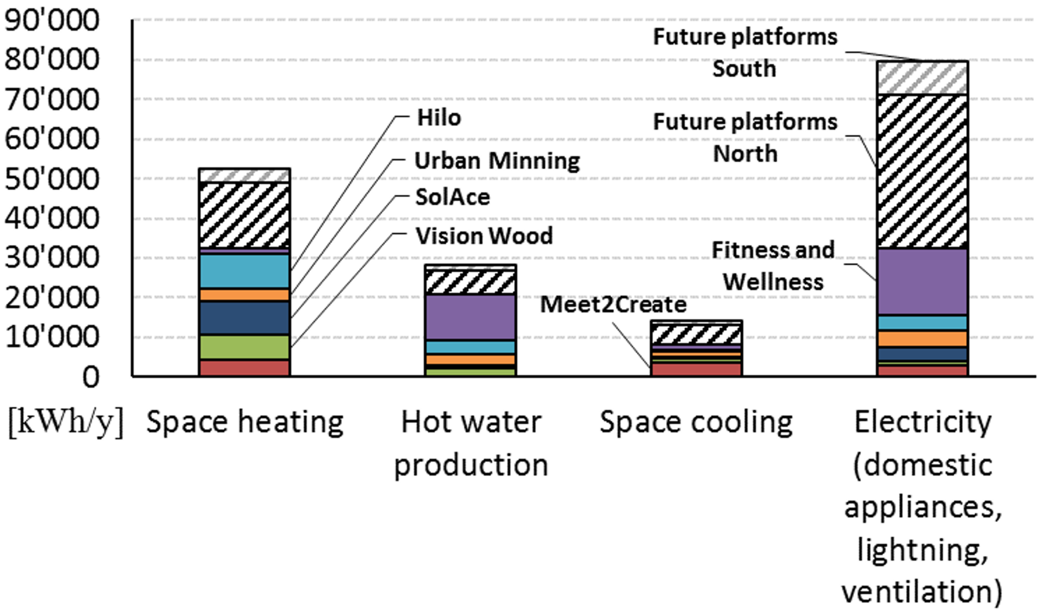

Figure 8: Yearly energy demand of the units in NEST

For each unit, a static Energy Signature model [8] and heating/cooling temperature curves [7] are integrated in order to obtain the monthly mean heating and cooling power. The model is calibrated on a typical meteorological year in Zurich–Kloten (Meteonorm [16]) with nominal sizing power for heating (at -9.9°C) and cooling (at 32.5°C). The cooling and domestic hot water sizing powers are compliant with the target values of the SIA standard 2024 [17]. The heating sizing powers are taken from existing energy simulations reports, or estimated on an annual basis considering a 2000-hour full heating load service per year.

## 5.1 Space heating and domestic hot water

The annual energy demand for space heating and domestic hot water with and the corresponding sizing powers are given in Table 4 below.

Table 4: Space heating and domestic hot water demand of existing and future units in NEST

| Unit | Ae | Space heating $Q_h$ kWh/y | $T_{h,c}$ °C | $P_h$ kW | Domestic hot water $Q_{dhw}$ kWh/y | $P_{dhw}$ kW |
|---|---|---|---|---|---|---|
| Meet2Create | 350 m$^2$ | 4'263 | 13.2 | 2.1 | 253 | 0.1 |
| Vision Wood | 152 m$^2$ | 6'245 | 12.4 | 3.3 | 2'111 | 0.7 |
| SFW | 275 m$^2$ | 2'266 | 13.3 | 1.1 | 15'687 | 5.0 |
| Hilo | 180 m$^2$ | 8'690 | 16.5 | 3.5 | 3'583 | 1.1 |
| Urban Minning | 194 m$^2$ | 3'359 | 13.2 | 1.7 | 2'782 | 0.9 |
| SolAce | 94 m$^2$ | 8'463 | 14.5 | 3.9 | 653 | 0.2 |
| **Total planned platforms** | **1'244 m$^2$** | **33'285** | | **15.6** | **25'069** | **8.0** |
| (Mean values) | | (26.7 kWh/m$^2$) | | (12.5 W/m$^2$) | (9.7 kWh/m$^2$) | (3.1 W/m$^2$) |
| Future platforms North | 616 m$^2$ | 16'479 | 14.1 | 7.7 | 5'963 | 1.9 |
| Future platforms South | 136 m$^2$ | 3'648 | 14.1 | 1.7 | 1'320 | 0.4 |
| **Total Future platforms** | **753 m$^2$** | **20'127** | | **9.4** | **7'283** | **2.3** |
| **Total NEST units** | **1'997 m$^2$** | **53'412** | | **25.0** | **32'352** | **10.4** |

## 5.2 Solar Fitness and Wellness – Sauna, steam bath and shower

Power, temperature levels and monthly operating time of the Solar Fitness and Wellness (SFW) Sauna, steam bath and shower of Table 5 and 6) are obtained from report [3].

Table 5: Saunna and steam bath installed power and temperature levels.

| Services | Finnish Saunna liquid | Bio Saunna liquid | Bio Saunna vapor | Steam bath liquid | Steam bath vapor | Shower liquid |
|---|---|---|---|---|---|---|
| Installed Power [kW] | 1.5 | 0.5 | 1.7 | 0.5 | 1.7 | 1.5 |
| Supply [ °$C$] | 120 | 70 | 85 | 60 | 85 | 50 |
| Return [ °$C$] | 60 | 40 | 40 | 40 | 40 | 10 |

Table 6: Wellness – openning hours per Month.

| J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 h | 120 h | 120 h | 120 h | 80 h | 40 h | 40 h | 0 h | 80 h | 120 h | 120 h | 100 h |

## 5.3 Space cooling

The annual energy demand for space cooling with the corresponding sizing power is given in Table 7 below.

Table 7: Cooling demand of existing and future units in NEST

| Unit | Ae | Space cooling<br>$Q_c$<br>kWh/y | <br>$T_{c,c}$<br>°C | <br>$P_c$<br>kW |
|---:|---:|---:|---:|---:|
| Meet2Create | 350 $m^2$ | 3'554 | 17.9 | 8.3 |
| Vision Wood | 152 $m^2$ | 1'065 | 17.1 | 2.1 |
| SFW | 275 $m^2$ | 2'898 | 13.3 | 3.2 |
| Hilo | 180 $m^2$ | 412 | 21.1 | 2.0 |
| Urban Minning | 194 $m^2$ | 1'377 | 17.5 | 3.0 |
| SolAce | 94 $m^2$ | 375 | 22.6 | 2.8 |
| **Total planned platforms**<br>(Mean values) | **1'244 $m^2$** | **9'680**<br>(7.8 kWh/$m^2$) | | **21.6**<br>(17.4 W/$m^2$) |
| Future platforms North | 616 $m^2$ | 4'793 | 14.1 | 10.7 |
| Future platforms South | 136 $m^2$ | 1'061 | 14.1 | 2.4 |
| **Total Future platforms** | **753 $m^2$** | **5'853** | | **13.1** |
| **Total NEST units** | **1'369 $m^2$** | **10'646** | | **23.8** |

## 5.4 Monthly energy demand

The aggregated monthly demand of the NEST units resulting from the simulation is shown in Figure 9.

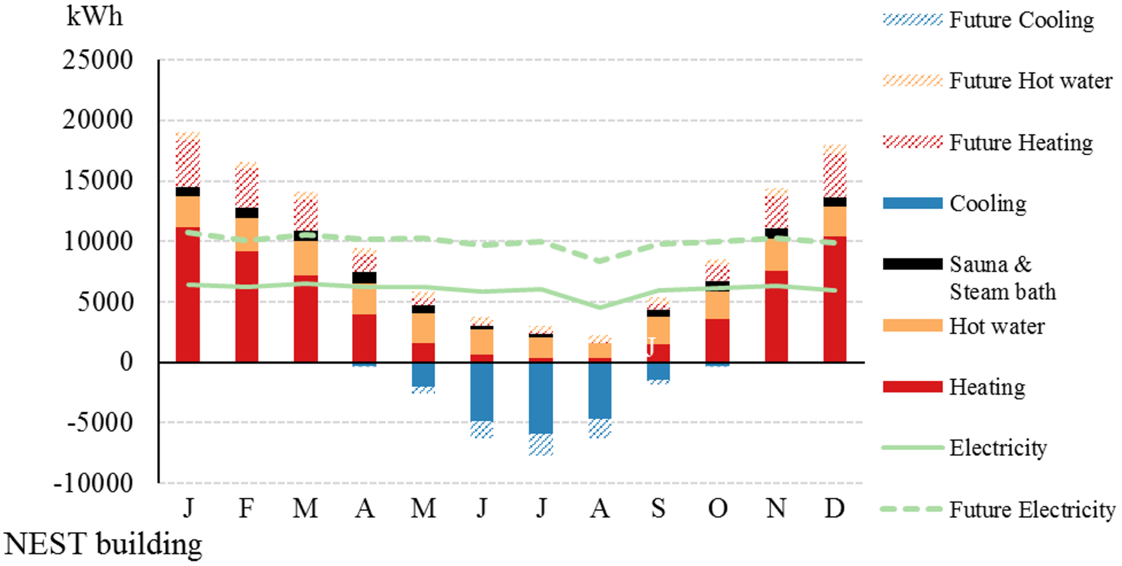

Figure 9: Aggregated monthly energy demand of the units in NEST

# 6 Scenario for the deployment of a $CO_2$ system in NEST

The $CO_2$ system demonstrator in NEST should be deployed through the technical galleries located on both sides of the NEST-Core building (Figure 10).

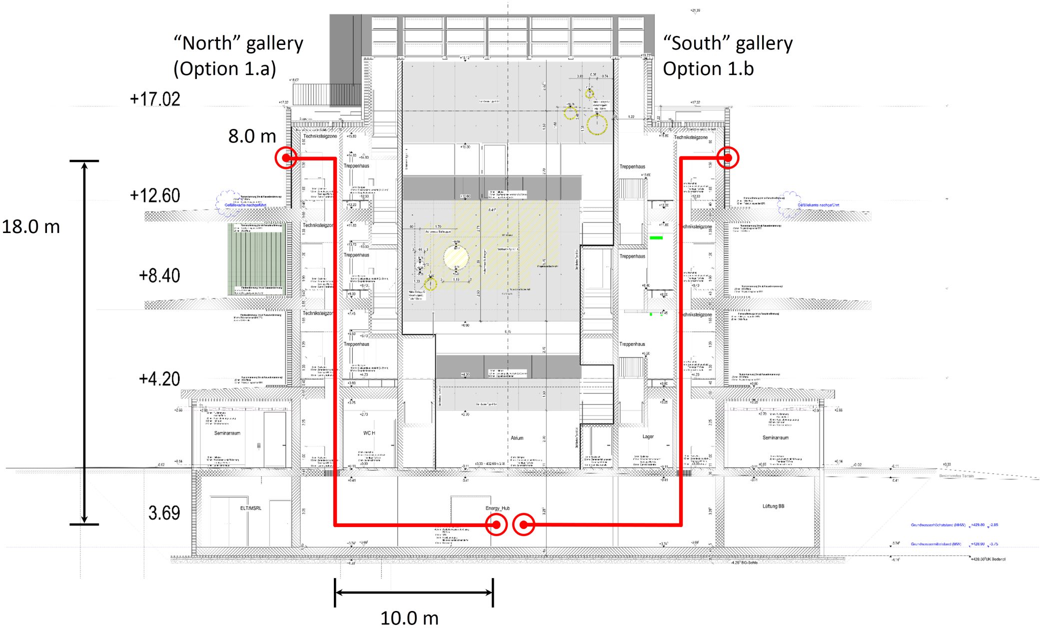

Figure 10: $CO_2$ distribution network in NEST with two options, through technical gallery "‘North"’ or "‘South"’.

## 6.1 Sizing thermal power

The sizing power for the "‘North"’ and "‘South"’ group of units is reported in Table 8.
The two basic scenarios consider the connection of the greatest heating and cooling consumers on each side of the building. On the "‘North"’ wing, it includes the "‘SFW"’ sauna, steam bath and associated shower for heating and a future unit (to be determined) for cooling (allegedly the one with the biggest floor area). On the "‘South"’ side it includes the unit "‘Solace"’ for heating and "‘Meet2Create"’ for cooling.
For each scenario the design power of the network is given by the overall sizing power requirements of planned and future units. On the "‘North"’ wing, this would represent 23.2 kW for heating and domestic hot water production through the $CO_2$ vapor line and 17.3 kW for cooling through the $CO_2$ liquid line. On the "‘South"’ wing, this would represent a total of 17.2 kW for heating and domestic hot water production in the $CO_2$ vapor line and 17.9 kW for cooling in the $CO_2$ liquid line.

Table 8: Basic and design loads for the first phase of a $CO_2$ network in NEST

| Gallery | Options | Units | Heating $P_h$ | dhw $P_{dhw}$ | Vapor line $P_{h+dhw}$ | Liquid line $P_c$ |
|---|---|---|---|---|---|---|
| North | I.3a-Basic | SFW* | 5.9 kW | 1.5 kW | 7.4 kW | – |
| | | Future unit | – | – | – | 3.4 kW |
| | | **Total** | 5.9 kW | 1.5 kW | **7.4 kW** | **3.4 kW** |
| | I.3a-Design | SFW | 1.1 kW | 5.0 kW | 6.2 kW | 3.2 kW |
| | | Future platforms North | 7.7 kW | 1.9 kW | 9.6 kW | 10.7 kW |
| | | **Total** | 14.8 kW | 8.4 kW | **23.2 kW** | **17.3 kW** |
| South | I.3b-Basic | Solace | 3.9 kW | – | 3.9 kW | – |
| | | Meet2Create | – | – | 0.0 kW | 8.3 kW |
| | | **Total** | 3.9 kW | 0.0 kW | **3.9 kW** | **8.3 kW** |
| | I.3b-Design | Vision Wood | 3.3 kW | 0.7 kW | 4.0 kW | 2.1 kW |
| | | Hilo | 3.5 kW | 1.1 kW | 4.6 kW | 2.0 kW |
| | | Urban Minning | 1.7 kW | 0.9 kW | 2.6 kW | 3.0 kW |
| | | Future platforms South | 1.7 kW | 0.4 kW | 2.1 kW | 2.4 kW |
| | | **Total** | 14.0 kW | 3.1 kW | **17.2 kW** | **17.9 kW** |

*(Sauna-Steam bath-Shower)

## 6.2 Conclusion

The analysis of the energy demand of §5, p.17 has shown that the overall sizing loads are about 23 kW for heating and 18 kW for cooling for each side ("'North"' and "'South"') of the building platformsda.

This study does not account for the benefits of connecting together "'North"' and "'South"' oriented units. However, as they are located on opposite corners/sides of the building (Figure 5), this connection would require the replication of the distribution system in both galleries. For simplicity, it is therefore reasonable to consider two options for the deployment of the $CO_2$ distribution network, either in the "'North"' (I.a) or "'South"' (I.b) technical gallery.

# 7 Concept of a $CO_2$ system in NEST

The concept of a $CO_2$ system in NEST is developed in the Table 9, p.23. The system is decomposed in four phases.

The first phase (I) comprises the minimum tasks required to demonstrate the operation of a $CO_2$ network, ie. the implementation of:

1. a central plant exchanging heat between the NEST mid-temperature (MT) and low-temperature (LT) DHC network to achieve the balance-of-plant of the $CO_2$ system (§7.1, p.24);
2. two lines for the distribution of $CO_2$ liquid and vapor (§7.2, p.24);
3. a decentralised heat exchanger bypassing the $CO_2$ heat pump (HP) evaporator of the SWF unit (Option I-3.a) or a decentralized HP for low temperature floor heating using the $CO_2$ network (Option I-3.b) (§7.3, p.25) or a $CO_2/CO_2$.
4. a decentralised $CO_2$/Air or water free cooling heat exchanger (§7.4, p.26).

Phase (I) is presented in greater detail in the remainder of this chapter. Its costing is given in (§8, 29) with a more detailed description in Annex D, pp.38–43.

Phase (II) would move towards an energy-autonomous system by introducing energy storage, model predictive control (MPC) and supercritical oil-free, open-loop, $CO_2$ heat pumps upgrading the $CO_2$ temperature at the right level for domestic hot water consumption.

Phase (III) would bring the demonstrator closer to real operating conditions by integrating a heat pump in the central plant, thus using solely the LT water network as a thermal source.

Phase (IV) would provide a link between the $CO_2$ system and the mobility system (Move) in NEST, in particular by recovering heat from the PEM fuel cell.

Table 9: Concept of $CO_2$ system in NEST

| Phase | Task (Option) | NEST Unit | Connection | Description | Equipment | Size min (Base) | Size max (Design) | Principle | Demonstration | Critical point |
|---|---|---|---|---|---|---|---|---|---|---|
| I | 1 | NEST basement | Central MT network (heating mode) and central LT network (cooling mode)/ CO2 network | **Central plant composed of 1 or 2 network/CO2 heat exchanger(s)** | - 2HX<br>- 2 B'ypass | Pliq.= 3.9 kW<br>Pvap.= 3.4 kW | Pliq.= 23.2 W<br>Pvap.= 3.9 kW | The heat exchanger allows to balance the CO2 network liquid and vapor lines using one or two heat exchangers in heating and cooling modes. Heat from the MT network will be injected in heating mode (vaporization of CO2) or removed in cooling mode (liquefaction of CO2). | **• CO2 district heating with vertical CO2 lines** | -pressurized equipment |
| | 2 | NEST Core | CO2 network | **Liquid and vapor CO2 distribution lines including pump valves ands surge tanks** | - pipes<br>- pump<br>- valves<br>- surge tank<br>- controller<br>- sensors | HH=14. 0m<br>L=32.0 m<br>Ø liq. = 12mm<br>Ø vap. = 15mm | HH=18. 2m<br>L=36.2 m<br>Ø liq. = 13mm<br>Ø vap. = 16mm | The CO2 liquid and vapor dsitribution lines run through from the besement to the 3rd floor through the technicak gallery. Design based on the experimental faclity in Geneva (SIG). | | - pressure drop in pipes<br>- pressurized equipment |
| | 3 (3.a) | SFW | CO2 network/CO2 heat pump | **CO2/CO2 heat exchanger for the supercritical CO2 heat pump bypassing the MT network and providing heat at 140°C for the sauna, steam bath and showers.** | - 1 HX<br>- 1 bypass<br>- 1 controller<br>- sensor | Pth= 7.4kW<br>Tdim=35-20/16 | | The CO2/CO2 heat exchanger is used as evaporator for the CO2 supercritical heat pump. A bypass will allow to switch the heat source of the supercritical CO2 heat pump from MT network (30°C) to CO2 network (16°C). | **• CO2 heat supply** | - the HP compressor shoud be able to compress CO2 from 16° instead of from 30°C<br>- greement of the HP manufacturer |
| | (3.b) | Solace | CO2 network/ heating substation | **Decentralised HP for low temperature floor heating using CO2 network** | - 1 HP<br>- 1 HX<br>- 1 bypass<br>- 1 controller<br>- sensor | Pth = 3.9 kW | | Conventional heat pump using CO2 netwok as a heat source (could also be cold/reversible?) to deliver heat to the low temperature floor heating system of the unit. Replacing the HP evaporator by a CO2 heat exchanger. | **• Decentralised closed loop heat pump** | - Space availability<br>- Possibility of usinghHigh speed compressor prorotype |
| | 4 (4.a) | Future unit | CO2 network/ cooling substation | **CO2/Air or water free cooling heat exchanger** | - 1 HX<br>- 1 bypass<br>- 1 controller<br>- sensor | Pth= 3.4 kW | | The heat exchanger provides free cooling by evaporating CO2 at 16°C from the liquid line to the vapor line. Parallel concept to the LT network connection. | **• CO2 heat recovery and free cooling** | |
| | (4.b) | Meet2Create | CO2 network/ cooling substation | **CO2/Air or water free cooling heat exchanger** | - 1 HX<br>- 1 bypass<br>- 1 controller<br>- sensor | Pth= 8.3 kW | | The heat exchanger provides free cooling by evaporating CO2 at 16°C from the liquid line to the vapor line. Parallel concept to the LT network connection. | **• CO2 heat recovery and free cooling** | |
| II | 1 | NEST basement | CO2 network | **Liquid and vapor CO2 tanks with model predictive control hardware** | - 2 tanks | Vliq= 60 L<br>Vvap= 20 L | Vliq= 150 L<br>Vvap= 25 L | The CO2 liquid and vapor storage are designd for daily energy storage. The model predictive on control module ensure the optimal operation of the stocks. | **• Integration of heat and cold storage**<br>**• MPC integration** | - pressurized equipment falling within categories III (<3000 bar·L) or IV (>3000 bar·L) of thepressure direcive (2014/68/EU) |
| | 2 | Future unit | CO2 network/ domestic hot water | **Supercritical open loop CO2 heat pump for hot water production** | - 1 HP<br>- 1 bypass<br>- 1 controller<br>- sensor | Pth= 0.5 kW | Pth= 5.0 kW | The open loop heat pump uses CO2 from the network to produce hot water using a supercritical oil-free compression cycle with direct reinjection in the CO2 liquid line. | **• Network is the evaporator of a decentralized CO2 heat pump** | - oil-free compressor technology<br>- open loop heat pump |
| III | 1 | NEST basement | LT network/ CO2 network | **Central heat pump on the LT network** | - 1 HP<br>- 1 bypass<br>- 1 controller<br>- sensor | Pth= 8.3 kW | Pth= 23.2 kW | Use of the LT network as a heat source for the open loop HP preparing the distributed CO2 in heating mode (substitute from the MT/CO2 network connection). | **• Network is the condenser of a centralized CO2 heat pump** | - centralized open loop heat pump |
| (VI) | 2 | Move | CO2 network/ cooling system of PEM and electrolyser | **PV, Electrolyser and PEM integration** | - pipes<br>- pump<br>- valves<br>- surge tanks<br>- controller<br>- sensors | L =150m | L =150m | Heat recovery from the PEM | **• Heat recovery - integration DHC with mobility** | - distance to the the NEST building |

## 7.1 Central plant

The central plant will collect medium-temperature and low-temperature water in the NEST MT network, and LT network. The configuration shown in Figure 11 allows to operate the water/$CO_2$ evaporative condenser in two modes. The proportional valve (1) and the flow meter (F) allow to control the hot and cold water flow rates. The other valves are closing and opening, depending on the selected mode of operation. In evaporating mode, MT water will flow through the counter current evaporative condensers. In condensing mode, valves will let LT water flow in. Note that the increase of temperature of the LT network involves shifting upward the pressure of the $CO_2$ network. Thus, the $CO_2$ system might fail to function in condensing mode for a cold water temperature greater than 20/15°C.

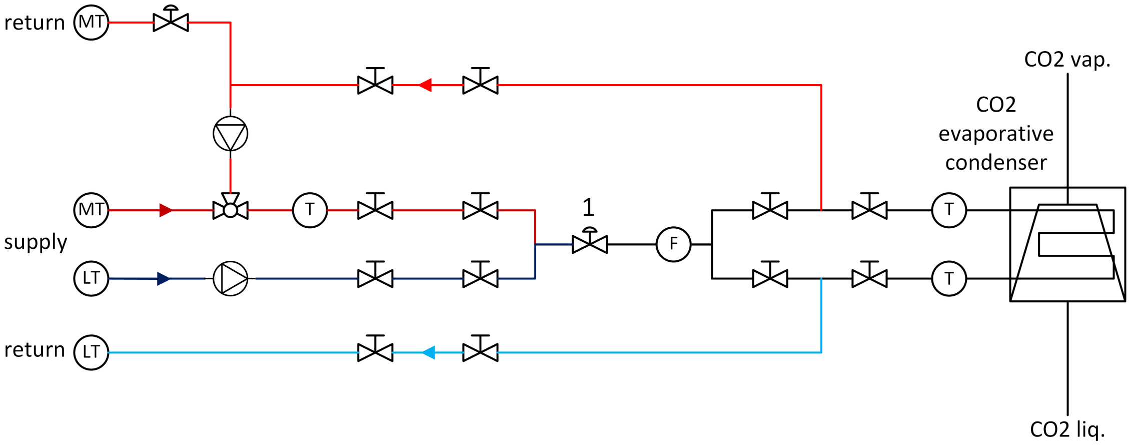

Figure 11: Hydraulic circuit diagram of the central plan.

## 7.2 $CO_2$ distribution network

The design point of the $CO_2$ distribution network is set to 52 bar, 11°C in the liquid line and 50 bar, 18°C in the vapor line. The $CO_2$ distribution network of Figure 12 can work in $CO_2$ evaporation mode (dashed line) and in $CO_2$ condensing mode (continuous line). In condensing mode the $CO_2$ is flowing from the vapor line, passing through a pressurizing pump to reach the liquid line.

With a pressure of 50 bar and the design specification of Table 8, the diameter of the pipe should be designed at 18mm for the vapor line and 11mm for the liquid line. This corresponds to a design velocity of 3 $m/s$ (0.6 $m/s$ in base load) in the liquid line and 1 $m/s$ (0.2 $m/s$ in base load) in the vapor line. This values account for hydraulic and friction pressure losses in pipes [2].

One can see in Annex C, p. 36-37, Figure 17 and 18 that the network does not fall under the pressure equipment directive (PED EC 2014/68 [4]) (sound engineering practice apply). However, in the vapor line, the design point is very close to the limit of 1000 bar·mm. Unless the design power set aside the future units, the network will be designed within the category (I) of the PED, where self-certification principles apply.

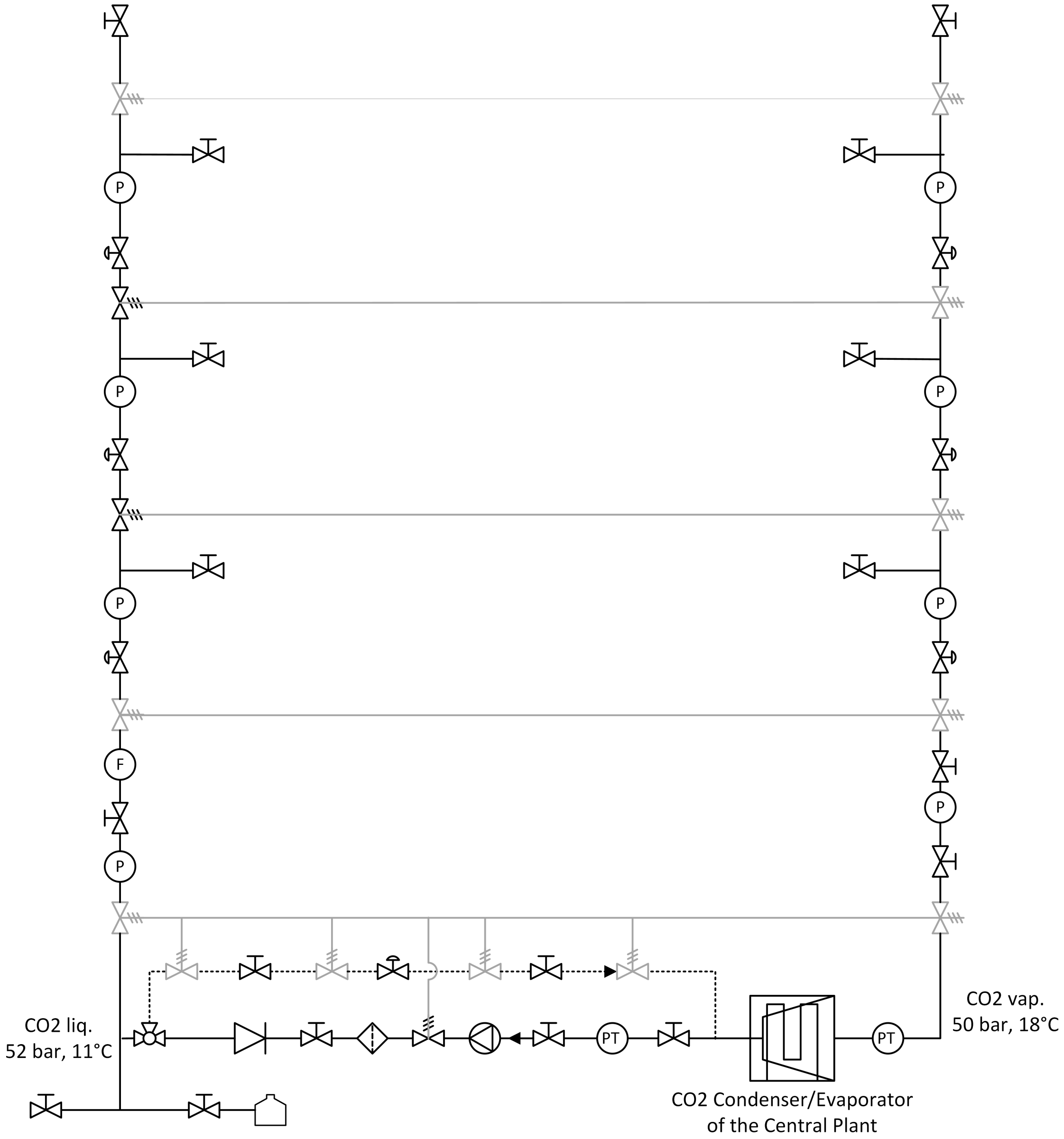

Figure 12: Hydraulic circuit diagram of the $CO_2$ distribution network in NEST.

## 7.3 Decentralised $CO_2$ heat exchanger/heat pump

The hydraulic circuit diagram of the decentralised $CO_2$ heat exchanger/heat pump is visible in Figure 13. Given an existing heat pump, the evaporator of the heat pump is retrofitted to be connected to the $CO_2$ network. On the other side, the MT water network is by-passed by the HP condenser.

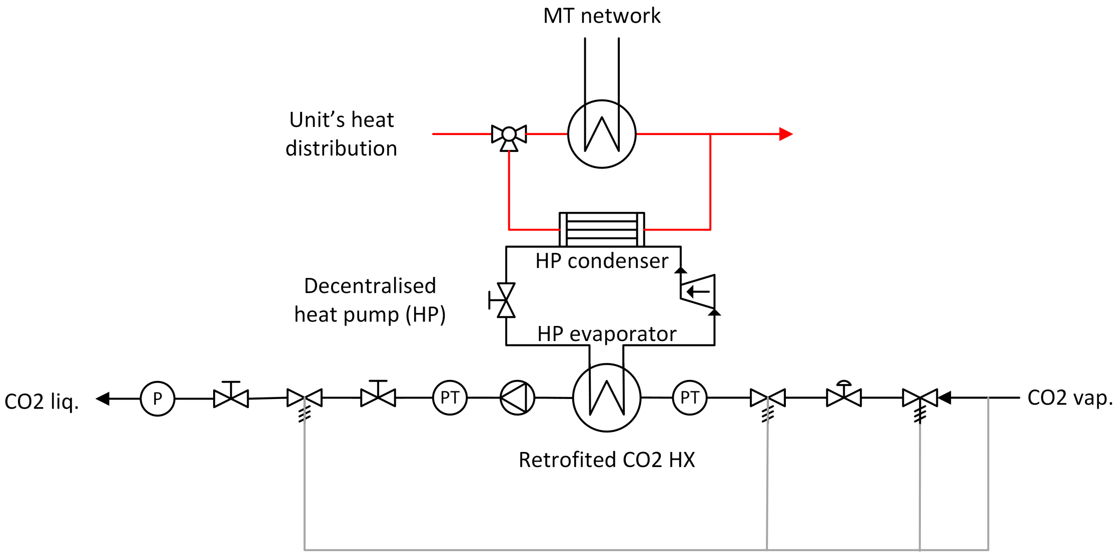

Figure 13: Hydraulic circuit diagram of the retrofitted heat pump $CO_2$ evaporator.

## 7.4 $CO_2$/Air or water free cooling heat exchanger

The hydraulic circuit diagram of the $CO_2$/Air (or water) free cooling heat exchanger is shown in Figure 14. A proportional valve controls the flow of liquid $CO_2$ that evaporates in the free cooling heat exchanger before reaching the vapor line of the network.

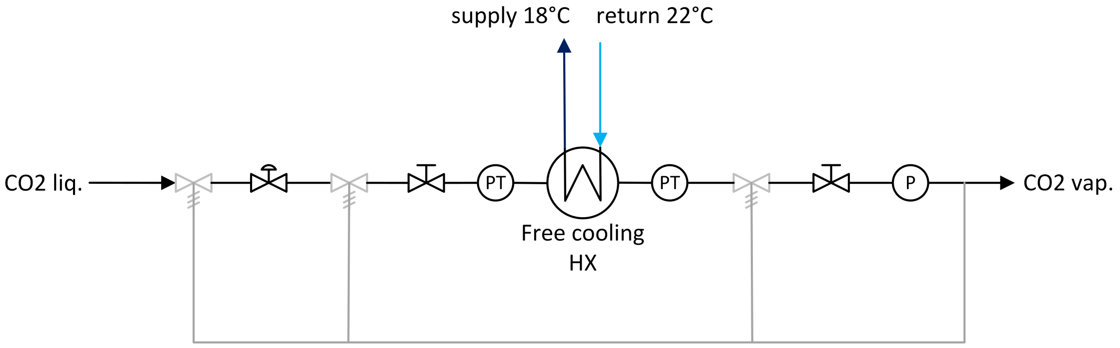

Figure 14: Hydraulic circuit diagram of the $CO_2$ free cooling heat exchanger.

## 7.5 Performance of the $CO_2$ system

The performance of the proposed $CO_2$ system in NEST has been estimated considering the basic scenario 1.(a) and 1.(b) of Table 8 with monthly simulation of the heating/cooling demand and thermodynamic model for:

- the $CO_2$ liquid and vapor line
- a supercritical (140°C) decentralized $CO_2$ HP (option I-3a)
- a decentralised R1234yf HP (option I-3b) for space heating and DHW production (option I-3b)

- a centralized R1234yf HP taking upgrading heat from LT network(T=10°C) to the $CO_2$ network

- photovoltaic (PV) panels and electricity storage. The simulation does not take into consideration the pumping consumption yet. Under theses conditions, the central HP reaches an annual COP 18.4, the decentralised heat pump for space heating a COP of 9.2 (I-3b) and the supercritical decentralized $CO_2$ HP a COP of 3.47. This leads to an annual electric consumption of 2510 $kWh_{el}$/year for option I-3a and 1230 $kWh_{el}$/year for option I-3b.

The system is energy autonomous (Figure 15 and 16) with 19.3/8.8 $m^2$ (option I-3a/I-3b) of PV cells coupled with an electricity storage of 1.25/0.86 kW (option I-3a/I-3b).

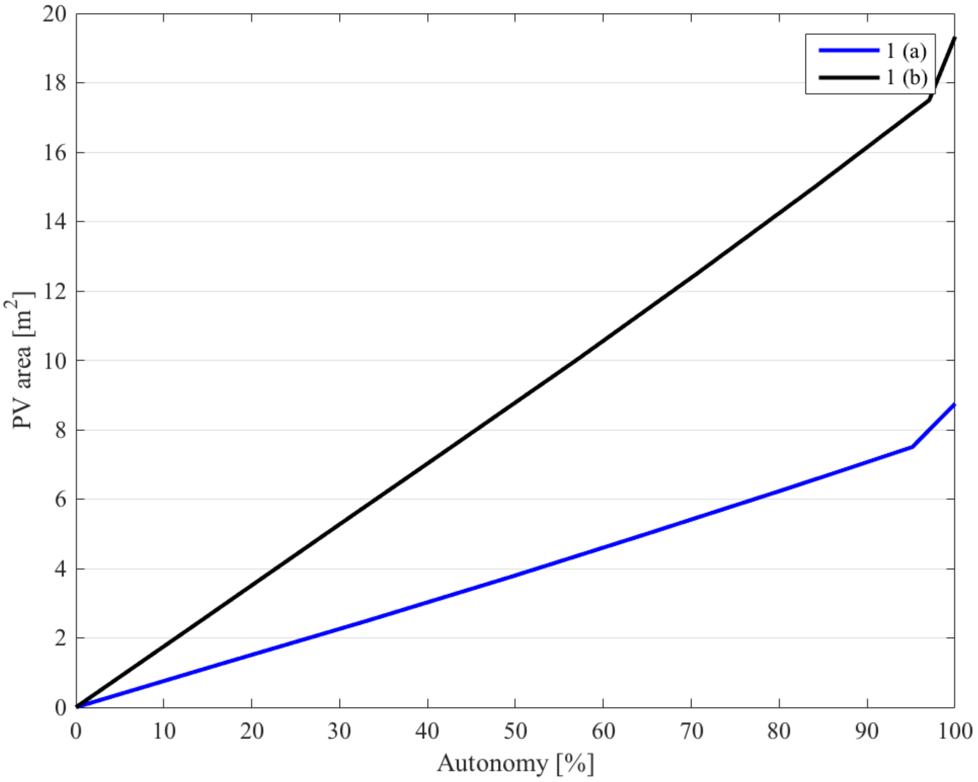

Figure 15: PV area as a function of the monthly energy autonomy of the $CO_2$ system.

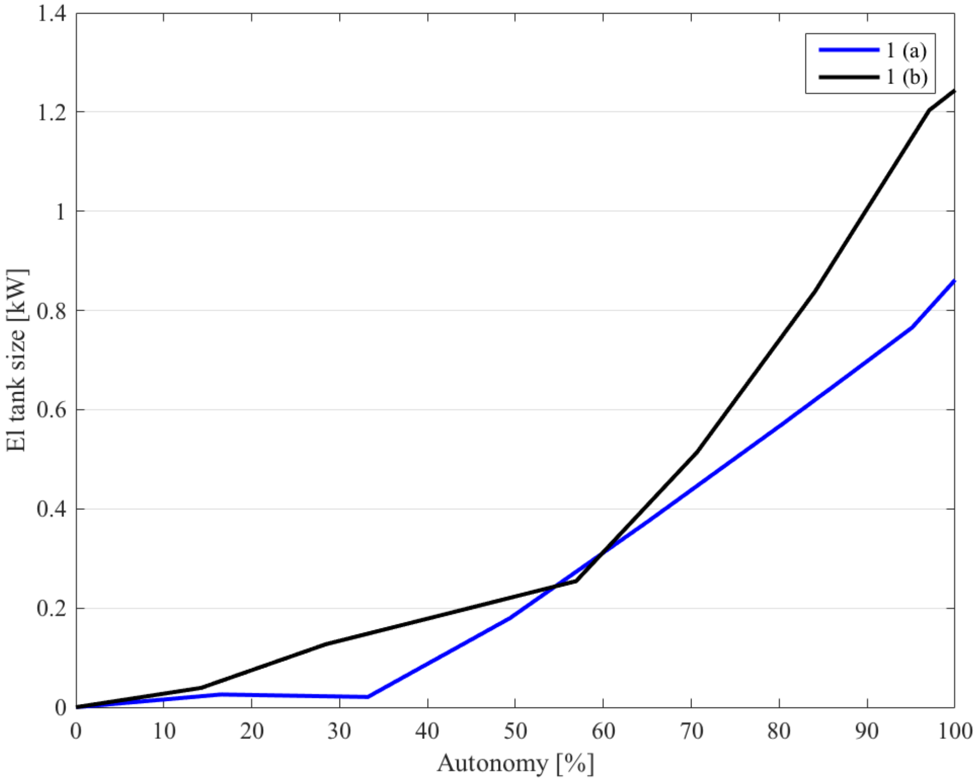

Figure 16: Electricity storage size as a function of the monthly energy autonomy of the $CO_2$ system.

# 8 Economic evaluation of a $CO_2$ system in NEST

The economic evaluation of the tasks of Phase (I) are given in Table 10. Further details for each task are given in Annex D, pp.38–43.
The cost of the system is estimated at 297'000.-CHF for the scenario which includes the retrofit/by-pass of the evaporator of the planned supercritical $CO_2$ heat pump of unit SFW (option I-3a) and 315'000 for the scenario considering the retrofit of the evaporator of a commercial heat pump for providing space heating (option I-3b).

Table 10: Economic evaluation of the deployment of a $CO_2$ system in NEST

| CO2 System in NEST | | |
|---|---|---|
| **Phase - Task** | **Description** | **Price CHF** |
| I.1 Central Plant heat exchanger(s) | | 97'000.0 |
| I.2 CO2 distribution network | | 65'000.0 |
| I.3a CO2/CO2 heat exchanger for the supercritical CO2 heat pump | | 61'000.0 |
| I.3b Decentralised HP for space heating using CO2 network | | 79'000.0 |
| I.4 CO2 free cooling heat exchanger | | 60'000.0 |
| Compressed air network | | 3'000.0 |
| Safety ventilation | | 5'000.0 |
| Conformity CE, PED... | | 6'000.0 |
| **Total phase I** | **Option a** | **297'000** |
| | **Option b** | **315'000** |

.

Considering a ratio on investment of 3.0% for the annual maintenance and a cost of 20 cts/kWh for electricity, the operation and maintenance cost is of the order of 10'000 CHF/year.

# 9 Conclusion

With 1'244 $m^2$, the existing/planned NEST units represent 62% of the floor energy area available on the NEST platforms. This constitutes a representative basis for the characterisation of the future units as well, providing a baseline for the design of the $CO_2$ system in NEST.
In the existing/planned NEST units, meeting rooms are occupying almost 1/3 of the space, offices 1/5 and sleeping rooms 1/10.

The analysis of the energy demand of §5, p.17 has shown that the overall sizing loads are about 23 kW for heating and 18 kW cooling for each side ("'North"' and "'South"') of the building platforms.

For simplicity, two options for the deployment of the $CO_2$ distribution network are considered: either in the "'North"' (option I-3a) or "'South"' (option I-3b) technical gallery. The first phase (I) of deployment of a $CO_2$ system in NEST would comprise the minimum tasks required to demonstrate the operation of a $CO_2$ network : a central plant, two lines for the distribution of $CO_2$ liquid and vapor, a decentralised heat exchanger bypassing the $CO_2$ heat pump (HP) evaporator of the SWF unit (Option I-3.a) or a decentralized HP for low temperature floor heating using the $CO_2$ network (Option I-3.b) and a decentralised $CO_2$/Air or water free cooling heat exchanger.

The system is energy autonomous (Figure 15 and 16) with 19.3/8.8 $m^2$ (option I-3a/I-3b) of PV cells coupled with an electricity storage of 1.25/0.86 kW (option I-3a/I-3b).

The cost of the system is estimated at 297'000.-CHF for the scenario which considers the retrofit/by-pass of the evaporator of the planned supercritical $CO_2$ heat pump of unit SFW (option I-3a) and 315'000 for the scenario which includes the retrofit of the evaporator of a commercial heat pump for providing space heating (option I-3b).
Considering a ratio on investment of 3.0% for the annual maintenance and a cost of 20 cts/kWh for electricity, the operation and maintenance cost is of the order of 10'000 CHF/year.

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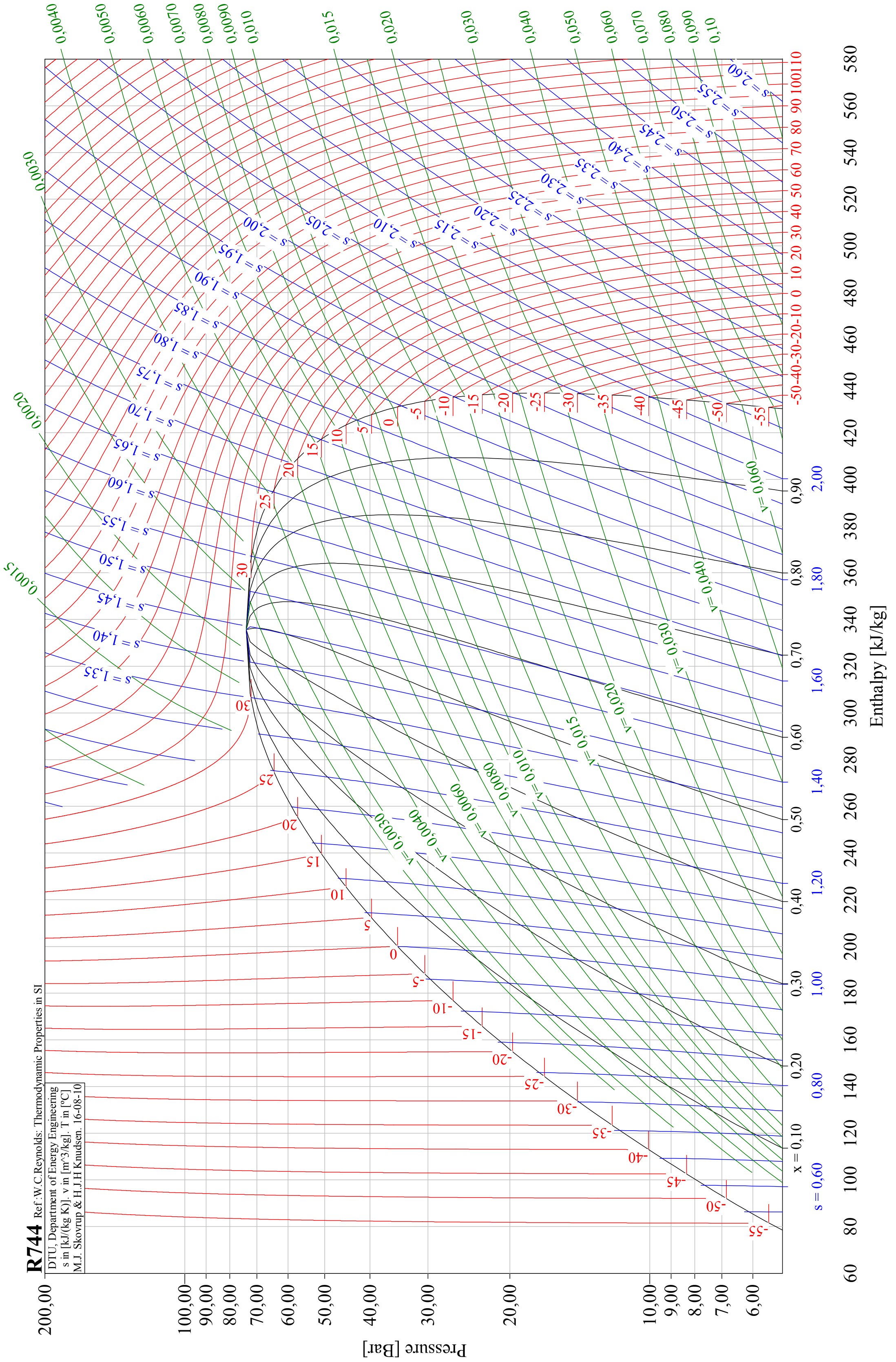
# Annex

# A CO$_2$ pressure-enthalpy diagram



# B Space utilisation in NEST units

Table 11: Useful ($A_u$) and energy ($A_e$) floor area (ratio of construction of 20% by default)

| Unit | Floor | Nr. (SIA 2024) | Room | Au (SIA 2024) | | Construction floor factor | Ae (SIA 380/1) |
|---|---|---|---|---|---|---|---|
| Nest Core | 0 | 12.1 | Backbone ohne UG | 1'000.0 $m^2$ | 1'500.0 $m^2$ | - | - |
| | | 4.5 | Untergeschoss (UG) | 500.0 $m^2$ | | | |
| Meet2Create | 1 | 3.3 | In-Out | 50.5 $m^2$ | 291.4 $m^2$ | 20.0% | 349.7 $m^2$ |
| | | 3.1 | Cocoon | 97.6 $m^2$ | | | |
| | | 3.3 | Hybrid | 143.3 $m^2$ | | | |
| Vision Wood | 2 | 3.1 | Residence | 44.8 $m^2$ | 119.2 $m^2$ | 27.5% | 152.0 $m^2$ |
| | | 12.6 | WC, bathroom | 10.8 $m^2$ | | | |
| | | 12.1 | Hall/corridor | 4.5 $m^2$ | | | |
| | | 6.2 | Common room | 29.5 $m^2$ | | | |
| | | 12.4 | Technical room | 13.5 $m^2$ | | | |
| | | 2.1 | Free | 16.1 $m^2$ | | | |
| Urban Minning | 2 | 2.1 | Bedroom | 68.8 $m^2$ | 161.8 $m^2$ | 20.0% | 194.2 $m^2$ |
| | | 3.1 | Kitchen, dining hall | 24.2 $m^2$ | | | |
| | | 3.3 | Meeting room | 24.2 $m^2$ | | | |
| | | 12.1 | Corridor | 6.2 $m^2$ | | | |
| | | 12.6 | Bathroom | 10.6 $m^2$ | | | |
| | | 12.7 | WC | 8.1 $m^2$ | | | |
| | | 12.4 | Storage | 6.8 $m^2$ | | | |
| | | 2.2 | Entrance hall | 13.0 $m^2$ | | | |
| SolAce | 2 | 2.1 | Hotel room | 8.2 $m^2$ | 78.7 $m^2$ | 19.4% | 94.0 $m^2$ |
| | | 3.1 | Small/openplan office | 32.3 $m^2$ | | | |
| | | 12.5 | Kitchen | 6.2 $m^2$ | | | |
| | | 3.3 | Meeting room | 27.6 $m^2$ | | | |
| | | 12.6 | WC, bathroom | 3.0 $m^2$ | | | |
| | | 12.4 | Annex room | 1.5 $m^2$ | | | |
| Hilo | 3 | 2.2 | Entry | 5.8 $m^2$ | 141.3 $m^2$ | 27.1% | 179.6 $m^2$ |
| | | 2.1 | Bedroom | 28.4 $m^2$ | | | |
| | | 12.6 | Ensuite | 11.4 $m^2$ | | | |
| | | 12.5 | Kitchen+Dinning | 24.3 $m^2$ | | | |
| | | 3.3 | Work/Live-Lounge | 35.4 $m^2$ | | | |
| | | 3.1 | Study | 22.0 $m^2$ | | | |
| | | 12.1 | Walkways/Gallery | 9.3 $m^2$ | | | |
| | | 12.3 | Stairs | 4.7 $m^2$ | | | |
| SFW | 3 | 11.2 | Fitness room | 60.0 $m^2$ | 266.0 $m^2$ | 3.4% | 275.0 $m^2$ |
| | | 12.6 | WC, bathroom | 30.0 $m^2$ | | | |
| | | 12.4 | Annex room | 10.0 $m^2$ | | | |
| | | 11.2 | Fitness room | 120.0 $m^2$ | | | |
| | | 2.2 | Reception Zone | 20.0 $m^2$ | | | |
| | | 12.5 | Kitchen | 20.0 $m^2$ | | | |
| | | 10.1 | Depot | 2.0 $m^2$ | | | |
| | | 12.7 | WC | 4.0 $m^2$ | | | |

# C $CO_2$ network piping design

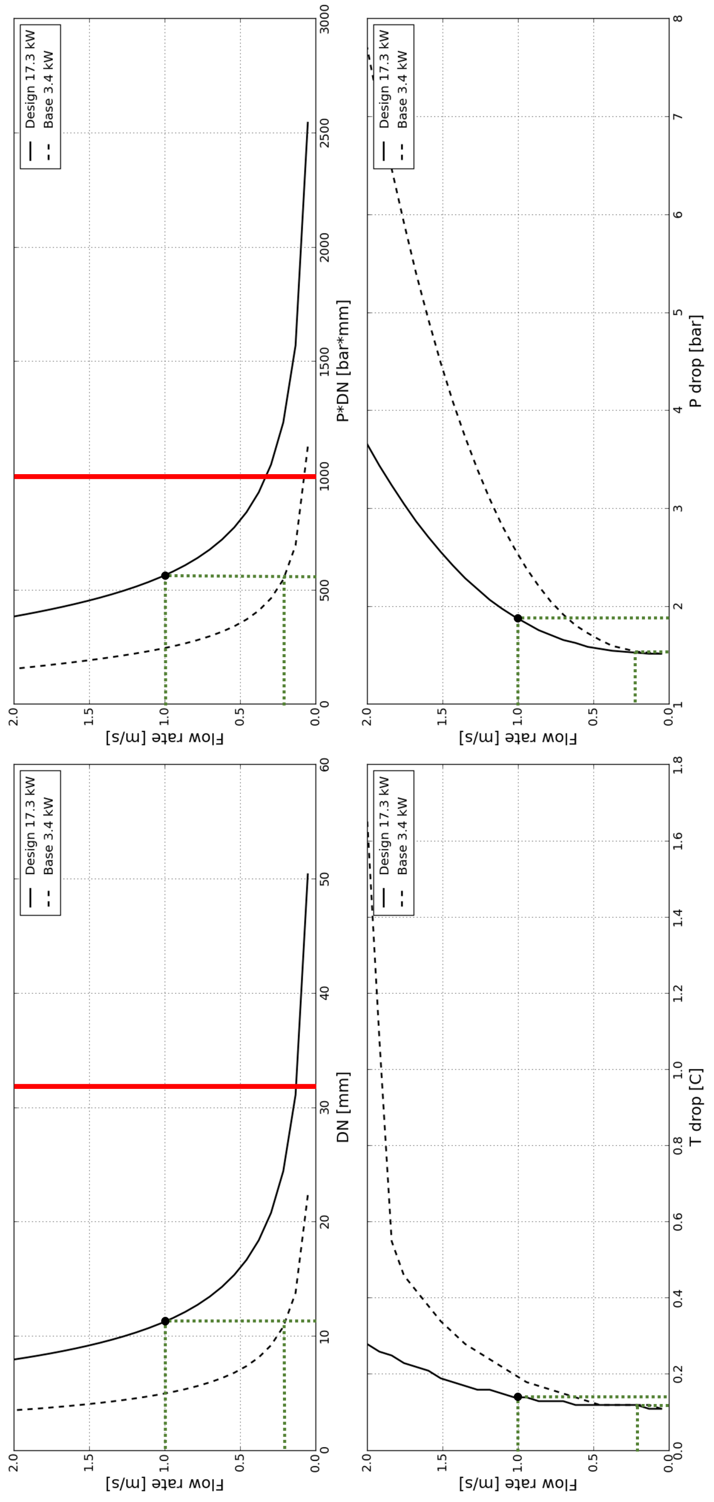


Figure 17: Design of the $CO_2$ liquid line at 52 bar, 11°C (design point in black – not subject to the PED [4] limit in red

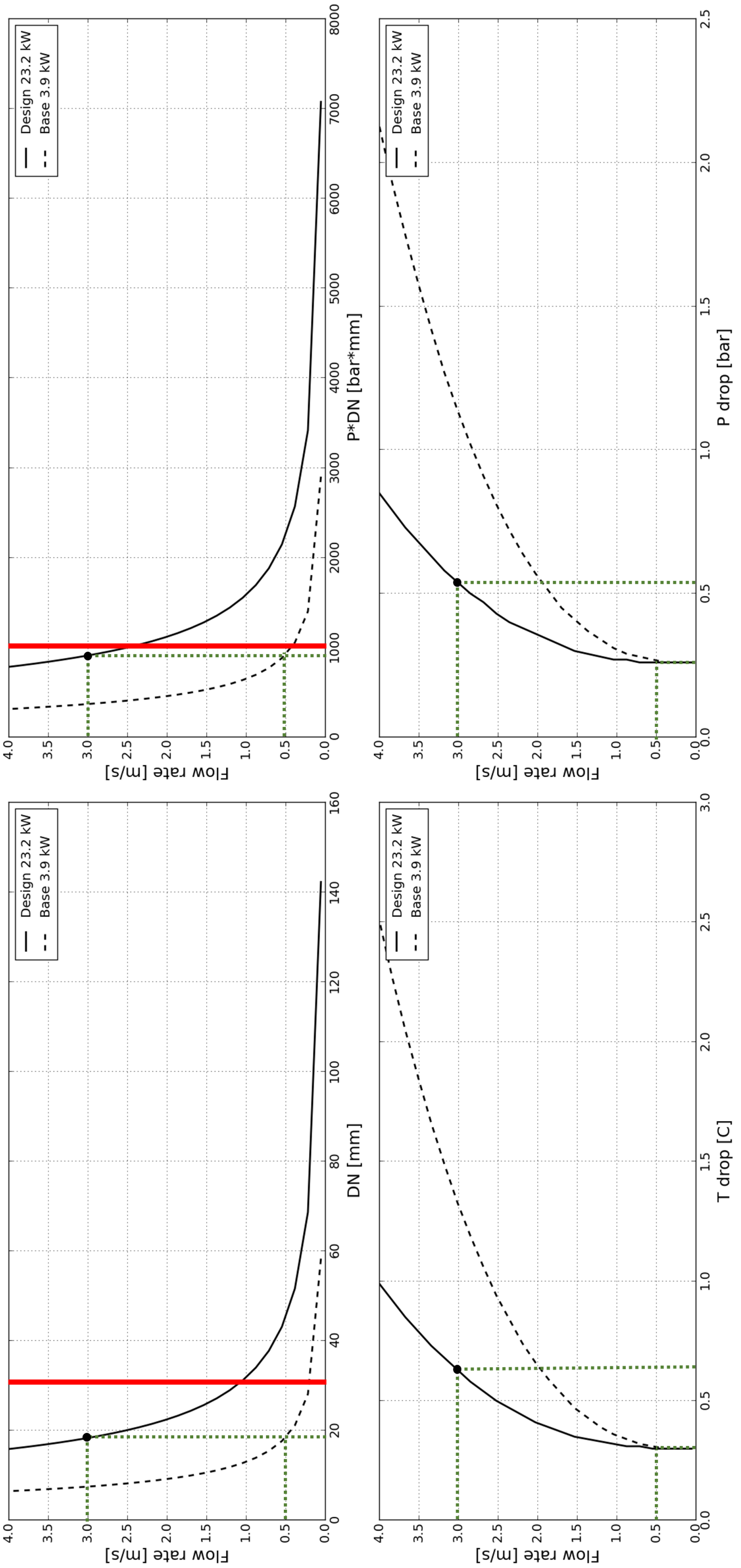


Figure 18: Design of the $CO_2$ vapor line at 50 bar, 18°C (design point in black – not subject to the PED [4]limit in red

# D Economic evaluation of a $CO_2$ system in NEST

| I.1 Central Plant heat exchanger(s) | | | | | | |
|---|---|---|---|---|---|---|
| | **Description** | **Supplier** | **Type** | **price CHF** | **quantity** | |
| Heating mode | CO2 condensate pump | Grundfoss | RC2-7 | 5'000.0 | 1 | 5'000 |
| | CO2 variable speed drive | Mitsubishi electric | FR-E740-095SC-EC | 875.0 | 1 | 875 |
| Cooling mode | CO2 heat exchanger (modified HP) | alfa laval | | 3'200.0 | 1 | 3'200 |
| | CO2 control valve | Refrigera/Belimo | spherique 3/4" moteur rapide | 795.0 | 4 | 3'180 |
| Control, data aquisition | temperature sensor | Roth+Co. | W020.4L.06,0X0050AB1 | 50.0 | 20 | 1'000 |
| | pressure transducer | Endress Hauser | Cerabar T PMP131 A70 | 176.0 | 8 | 1'408 |
| | differential pressure transducer | Endress Hauser | Deltabar S PMD75 | 2'005.0 | 4 | 8'020 |
| | flowmeter CO2/refr. HP | No info yet | | 7'000.0 | 2 | 14'000 |
| | flowmeter hot water/cold water | Aquametro | Topas pmg | 500.0 | 4 | 2'000 |
| | PLC | WAGO or NI | | 20'000.0 | 1 | 20'000 |
| Safety | Gas leak detection | gasalarm | | 2'500.0 | 1 | 2'500 |
| | Pressure switch | Baumer | RP2N | 272.0 | 3 | 816 |
| | Pressure relief valves | Nova Generali | | 120.0 | 4 | 480 |
| | CO2 Filter/dehumidifier | MP filtri | | 400.0 | 1 | 400 |
| | check valve 3.5 bar | Swagelok | | 171.0 | 4 | 684 |
| Servicing and maintenance | ball valve hand operated | refrigera | | 450.0 | 4 | 1'800 |
| | check valve | Swagelok | | 171.0 | 2 | 342 |
| | CO2 sightglass | refrigera | | 202.0 | 8 | 1'616 |
| Assembly | hours of work | | | 100.0 | 300 | 30'000 |
| **Total** | | | | | | **97'000** |

| I.2 CO2 distribution network | | | | | | |
|---|---|---|---|---|---|---|
| | **Description** | | | **Price** | **quantity** | |
| Network piping liquid CO2 | 1" diameter | | | 35.0 | 36 m | 1'260 |
| Network piping vapour CO2 | 1" diamter | | | 35.0 | 36 m | 1'260 |
| network sectioning valves and acessories | | | | 32'000.0 | 1 | 32'000 |
| Construction work of the pipelines | | | | 100.0 | 300 | 30'000 |
| **Total** | | | | | | **65'000** |

### I.3a CO2/CO2 heat exchanger for the supercritical CO2 heat pump

| | Description | Supplier | Type | price CHF | quantity | |
|---|---|---|---|---|---|---|
| Heat exchanger | CO2 heat exchanger (modified HP) | alfa laval | CBX P52 - 106 | 1'655.0 | 2 | 3'310 |
| | CO2 control valve | Refrigera/Belimo | spherique 3/4" moteur rapide | 795.0 | 2 | 1'590 |
| | Bypass | | | 1'000.0 | 1 | 1'000 |
| Control, data aquisition | temperature sensor | Roth+Co. | W020.4L.06,0X0050AB1 | 50.0 | 16 | 800 |
| | pressure transducer | Endress Hauser | Cerabar T PMP131 A70 | 176.0 | 6 | 1'056 |
| | differential pressure transducer | Endress Hauser | Deltabar S PMD75 | 2'005.0 | 3 | 6'015 |
| | flowmeter CO2/refr. HP | No info yet | No info yet | 7'000.0 | 2 | 14'000 |
| | flowmeter hot water/cold water | Aquametro | Topas pmg | 500.0 | 3 | 1'500 |
| | PLC | WAGO or NI | No info yet | 7'000.0 | 1 | 7'000 |
| Safety | Gas leak detection | gasalarm | No info yet | 2'500.0 | 1 | 2'500 |
| | Pressure switch | Baumer | RP2N | 272.0 | 3 | 816 |
| | Pressure relief valves | Nova Generali | | 120.0 | 6 | 720 |
| | CO2 Filter/dehumidifier | MP filtri | | 400.0 | 2 | 800 |
| | check valve 3.5 bar | Swagelok | | 171.0 | 6 | 1'026 |
| Servicing and maintenance | ball valve hand operated | refrigera | | 450.0 | 6 | 2'700 |
| | check valve | Swagelok | | 171.0 | 1 | 171 |
| | CO2 sightglass | refrigera | | 202.0 | 4 | 808 |
| Assembly | hours of work | | | 100.0 | 150 | 15'000 |
| **Total** | | | | | | **61'000** |

### I.3b Decentralised HP for space heating using CO2 network

| | Description | Supplier | Type | price CHF | quantity | |
|---|---|---|---|---|---|---|
| Heating | Heat pump | Waterkotte | EcoTouch Ai1 Geo 5006.5 | 13'825.0 | 1 | 13'825 |
| | CO2 condensate pump | Grundfoss | RC2-7 | 5'000.0 | 1 | 5'000 |
| | CO2 variable speed drive | Mitsubishi electric | FR-E740-095SC-EC | 875.0 | 1 | 875 |
| | Evaporator/condensor | Alfa Laval | | 4'000.0 | 1 | 4'000 |
| | Heat pump retrofit | | | 100.0 | 42 | 4'200 |
| Control, data aquisition | temperature sensor | Roth+Co. | W020.4L.06,0X0050AB1 | 50.0 | 12 | 600 |
| | pressure transducer | Endress Hauser | Cerabar T PMP131 A70 | 176.0 | 4 | 704 |
| | differential pressure transducer | Endress Hauser | Deltabar S PMD75 | 2'005.0 | 2 | 4'010 |
| | flowmeter CO2/refr. HP | No info yet | No info yet | 7'000.0 | 2 | 14'000 |
| | flowmeter hot water/cold water | Aquametro | Topas pmg | 500.0 | 2 | 1'000 |
| | PLC | WAGO or NI | No info yet | 7'000.0 | 1 | 7'000 |
| Safety | Gas leak detection | gasalarm | No info yet | 4'000.0 | 1 | 4'000 |
| | Pressure switch | Baumer | RP2N | 272.0 | 3 | 816 |
| | Pressure relief valves | Nova Generali | | 120.0 | 4 | 480 |
| | CO2 Filter/dehumidifier | MP filtri | | 400.0 | 1 | 400 |
| | check valve 3.5 bar | Swagelok | | 171.0 | 4 | 684 |
| Servicing and maintenance | ball valve hand operated | refrigera | | 450.0 | 4 | 1'800 |
| | check valve | Swagelok | | 171.0 | 1 | 171 |
| | CO2 sightglass | refrigera | | 202.0 | 4 | 808 |
| Assembly | hours of work | | | 100.0 | 150 | 15'000 |
| **Total** | | | | | | **79'000** |

## I.4 CO2 free cooling heat exchanger

| | Description | Supplier | Type | price CHF | quantity | |
|---|---|---|---|---|---|---|
| | CO2 heat exchanger (free cooling) | alfa laval | CBX P52 - 106 | 1'655.0 | 2 | 3'310 |
| | CO2 control valve | Refrigera/Belimo | spherique 3/4" moteur rapide | 795.0 | 2 | 1'590 |
| Control, data aquisition | temperature sensor | Roth+Co. | W020.4L.06,0X0050AB1 | 50.0 | 16 | 800 |
| | pressure transducer | Endress Hauser | Cerabar T PMP131 A70 | 176.0 | 6 | 1'056 |
| | differential pressure transducer | Endress Hauser | Deltabar S PMD75 | 2'005.0 | 3 | 6'015 |
| | flowmeter CO2/refr. HP | No info yet | No info yet | 7'000.0 | 2 | 14'000 |
| | flowmeter hot water/cold water | Aquametro | Topas pmg | 500.0 | 3 | 1'500 |
| | PLC | WAGO or NI | No info yet | 7'000.0 | 1 | 7'000 |
| Safety | Gas leak detection | gasalarm | No info yet | 2'500.0 | 1 | 2'500 |
| | Pressure switch | Baumer | RP2N | 272.0 | 3 | 816 |
| | Pressure relief valves | Nova Generali | | 120.0 | 6 | 720 |
| | CO2 Filter/dehumidifier | MP filtri | | 400.0 | 2 | 800 |
| | check valve 3.5 bar | Swagelok | | 171.0 | 6 | 1'026 |
| Servicing and maintenance | ball valve hand operated | refrigera | | 450.0 | 6 | 2'700 |
| | check valve | Swagelok | | 171.0 | 1 | 171 |
| | CO2 sightglass | refrigera | | 202.0 | 4 | 808 |
| Assembly | hours of work | | | 100.0 | 150 | 15'000 |
| **Total** | | | | | | **60'000** |

| II CO2 tanks and MPC hardware | | | | | | |
|---|---|---|---|---|---|---|
| | **Description** | **Supplier** | **Type** | **price CHF** | **quantity** | |
| Tank | CO2 liqui tank | | | 10'000.0 | 1 | 10'000 |
| | CO2 vapor tank | | | 10'000.0 | 1 | 10'000 |
| **Total** | | | | | | **20'000** |

| III Central plant | | | | | | |
|---|---|---|---|---|---|---|
| | **Description** | **Supplier** | **Type** | **price CHF** | **quantity** | |
| Heating | water - CO2 HP | Waterkotte | ET027505AiW | 15'624.0 | 2 | 31'248 |
| | CO2 condensate pump | Grundfoss | RC2-7 | 5'000.0 | 2 | 10'000 |
| | CO2 variable speed drive | Mitsubishi electric | FR-E740-095SC-EC | 875.0 | 2 | 1'750 |
| Cooling | CO2 heat exchanger (modified HP) | alfa laval | CBX P52 - 106 | 1'655.0 | 4 | 6'620 |
| | CO2 heat exchanger (free cooling) | alfa laval | CBX P52 - 106 | 1'655.0 | 4 | 6'620 |
| | CO2 control valve | Refrigera/Belimo | spherique 3/4" moteur rapide | 795.0 | 4 | 3'180 |
| Control, data aquisition | temperature sensor | Roth+Co. | W020.4L.06,0X0050AB1 | 50.0 | 20 | 1'000 |
| | pressure transducer | Endress Hauser | Cerabar T PMP131 A70 | 176.0 | 8 | 1'408 |
| | differential pressure transducer | Endress Hauser | Deltabar S PMD75 | 2'005.0 | 4 | 8'020 |
| | flowmeter CO2/refr. HP | No info yet | No info yet | 7'000.0 | 2 | 14'000 |
| | flowmeter hot water/cold water | Aquametro | Topas pmg | 500.0 | 4 | 2'000 |
| | PLC | WAGO or NI | No info yet | 20'000.0 | 1 | 20'000 |
| Safety | Gas leak detection | gasalarm | No info yet | 4'000.0 | 1 | 4'000 |
| | Pressure switch | Baumer | RP2N | 272.0 | 3 | 816 |
| | Pressure relief valves | Nova Generali | | 120.0 | 4 | 480 |
| | CO2 Filter/dehumidifier | MP filtri | | 400.0 | 1 | 400 |
| | check valve 3.5 bar | Swagelok | | 171.0 | 4 | 684 |
| Servicing and maintenance | ball valve hand operated | refrigera | | 450.0 | 4 | 1'800 |
| | check valve | Swagelok | | 171.0 | 2 | 342 |
| | CO2 sightglass | refrigera | | 202.0 | 8 | 1'616 |
| Assembly | hours of work | | | 100.0 | 200 | 20'000 |
| **Total** | | | | | | **136'000** |

**CO2 System in NEST**

| Phase - Task | Description | Price CHF |
|---|---|---|
| I.1 Central Plant heat exchanger(s) | | 97'000.0 |
| I.2 CO2 distribution network | | 65'000.0 |
| I.3a CO2/CO2 heat exchanger for the supercritical CO2 heat pump | | 61'000.0 |
| I.3b Decentralised HP for space heating using CO2 network | | 79'000.0 |
| I.4 CO2 free cooling heat exchanger | | 60'000.0 |
| Compressed air network | | 3'000.0 |
| Safety ventilation | Operated in case of leak | 5'000.0 |
| Conformity CE, PED… | | 6'000.0 |
| **Total phase I** | **Option a** | **297'000** |
| | **Option b** | **315'000** |
| II CO2 tanks and MPC hardware | | 20'000.0 |
| Conformity CE, PED… | | 6'000.0 |
| **Total phase II** | | **26'000** |
| III Central plant | | 136'000.0 |
| Conformity CE, PED… | | 6'000.0 |
| **Total phase III** | | **142'000** |
| **Total phase I-II-III** | **Option a** | **465'000** |
| | **Option b** | **483'000** |