7

Applying Advanced Technical Concepts to Selected Scenarios

Verena Rudolf[1], Nirendra Lal Shrestha[1], Eduard Oró[2], Thorsten Urbaneck[1] and Jaume Salom[2]

[1]Chemnitz University of Technology,
Professorship Technical Thermodynamics, Germany
[2]Catalonia Institute for Energy Research – IREC, Spain

7.1 Overview of Concept Performance

In this section, the energetic and economic performance of the concepts are analysed varying the main Data Centre's characteristics. To do so, the following metrics are used (see Chapter 3 for a detailed description):

- Normalized[1] non-renewable Data Centre primary energy ($PE_{DC,nren}/Nominal\ IT\ Power$)
- Normalized CAPEX ($CAPEX/Nominal\ IT\ Power$)
- Normalized OPEX ($OPEX/Nominal\ IT\ Power$)
- Normalized total cost of ownership ($TCO/Nominal\ IT\ Power$)
- Power usage effectiveness (PUE)
- Renewable energy ratio (RER)

TRNSYS [1] simulations over an entire year are used to investigate the performance of each concept. This software is mainly used to model and simulate systems that are influenced by several independent factors and that involve non-cyclical storage processes. It offers a broad variety of standard components such as pumps, buildings, wind turbines, weather data processor etc. and has capabilities to import components from other libraries, for example, TESS, Transsolar, etc. The performance of the models with respect to the variation of some of the most important parameters such as the location

[1]A normalized metric means that the standard metric is divided by the IT power capacity of the Data Centre in kW.

and size of the Data Centre is investigated using the Monte Carlo[2] sampling of the parameter space. For this, 100 simulations with a duration of one year were performed in order to generate the results. As described, one of the most important parameters is the location, which is one of the driving force behind the results. The location determines many input variables of the simulation that affects the system performance. The most important ones are:

- Environmental conditions, strongly related with free cooling potential;
- Electricity price profile;
- Share of renewables in the electricity grid.

Therefore, in this section, the performance of each concept is investigated considering the different locations. For the analysis of the concepts, 26 different locations within Europe have been considered (Table 7.1). These European cities were selected taking into account the climate zones as proposed in Köppen climate classification [2], such as dry, temperate, continental, polar and tropical climates. During the simulation, the other parameters of each concept are unchanged.

Figure 7.1 to Figure 7.6 show the box plots[3] for the different metrics. Different colours categorize the concepts. Green is used for the concept with renewable energy sources (concept 1), purple shows the concept with thermal end electrical storage (concept 4), red is used for concepts with CHP systems (concepts 5 and 6) and the other concepts are marked in blue (concepts 2 and 3).

Notice that the energy metrics would change drastically in function of the fuel used to produce the cooling in the district heating and cooling plant or the fuel used in the CHP plant. Table 7.2 shows the average normalized ratios for primary energy for European countries.

Figure 7.1 shows the boxplots of the distribution of the non-renewable primary energy consumption per nominal IT power for each advanced solution analysed. The higher value of this metric represents the higher impact on the environment. The median value of the primary energy consumption is different for all the concepts. Concept 4 has the highest median values indicating the highest primary energy consumption, because the concept does not incorporate any renewable energy generation, only storage (both, electrical and thermal). Concepts 5 and 6 have the lowest values, because

[2]Monte Carlo method is a broad class of computational algorithm that rely on repeated random sampling to obtain numerical results.

[3]Boxplots are a very compact way to visualize data. The dots represent outliers. The vertical line at the bottom is the bottom quartile of the data, the box itself covers the 2nd and 3rd quartile and the vertical line on top of the box covers the top quartile of the data.

Table 7.1 European cities selected for the concept analysis

City		Country	Climate Zone
Almeria	ALM	Spain	Dry
Madrid	MAD	Spain	Dry
Valencia	VAL	Spain	Dry
Bergen	BGO	Norway	Polar and Alpine
Innsbruck	INN	Austria	Polar and Alpine
Zurich	ZRH	Switzerland	Polar and Alpine
Belgrade	BEG	Serbia	Continental
Kaunas	KUN	Lithuania	Continental
Kiev	KBP	Ukraine	Continental
Stockholm	STK	Sweden	Continental
Warsaw	WAW	Poland	Continental
Amsterdam	AMS	The Netherlands	Temperate
Barcelona	BCN	Spain	Temperate
Edinburgh	EDI	Scotland	Temperate
Frankfurt	FRA	Germany	Temperate
Milano	MIL	Italy	Temperate
London	LON	UK	Temperate
Paris	PAR	France	Temperate
Porto	OPO	Portugal	Temperate
Seville	SVQ	Spain	Temperate
Chemnitz	CHE	Germany	Temperate
Roma	ROM	Italy	Temperate
Verona	VER	Italy	Temperate
Groningen	GRO	Netherlands	Temperate
Rotterdam	ROT	Netherlands	Temperate
Ancona	ANC	Italy	Temperate

Table 7.2 Primary and final energy and CO_2 emissions conversion factors

Energy Source	Non-Renewable Primary Energy Weighting Factor [3]	Total Primary Energy Weighting Factor [3]
PV	0.00	1.00
Wind	0.00	1.00
Biogas	0.50	1.50
Biomass	0.05	1.05
District cooling[4]	0.60	1.70
Exported heat	0.70	2.00

[4]District cooling primary Energy and CO_2 emission factors are dependent of the energy used and the district heating and cooling network. In the study, the factors are the ones from Parc de l'Alba [4] district network.

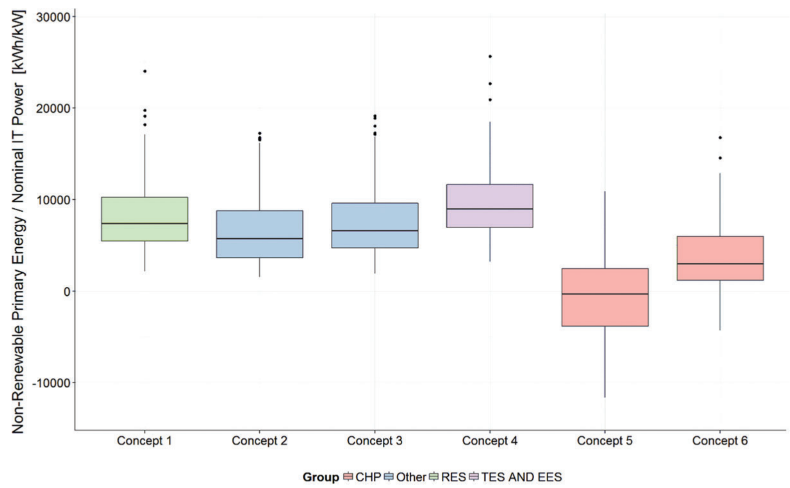


Figure 7.1 Evaluation of the concepts with respect to the non-renewable primary energy/nominal IT power.

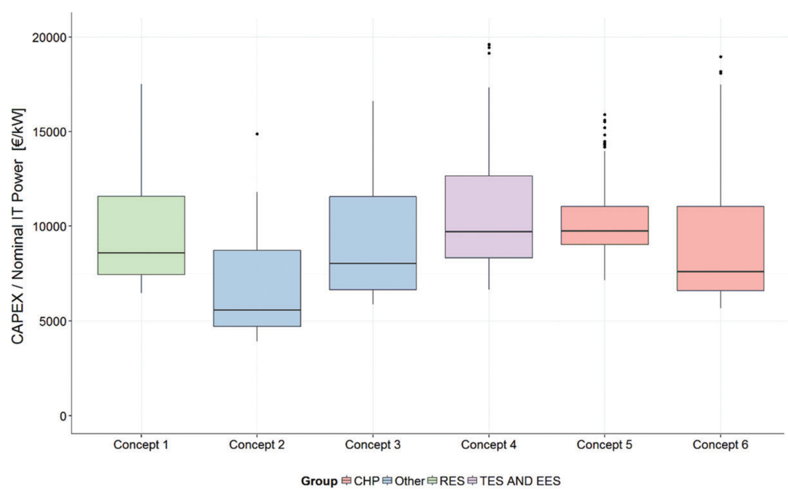


Figure 7.2 Evaluation of the concepts with respect to the CAPEX/nominal IT power.

the energy generated by the CHP plant has a very low non-renewable primary energy factor due to the fuels used and a complete re-use of the excess of heat produced by the CHP and not used by the Data Centre itself. The negative value of the primary energy consumption (concept 5) represents bigger generation of the primary energy than required for the Data Centre and thus, an export of the excess energy. Therefore, since the excess of energy is exported, concept 1,

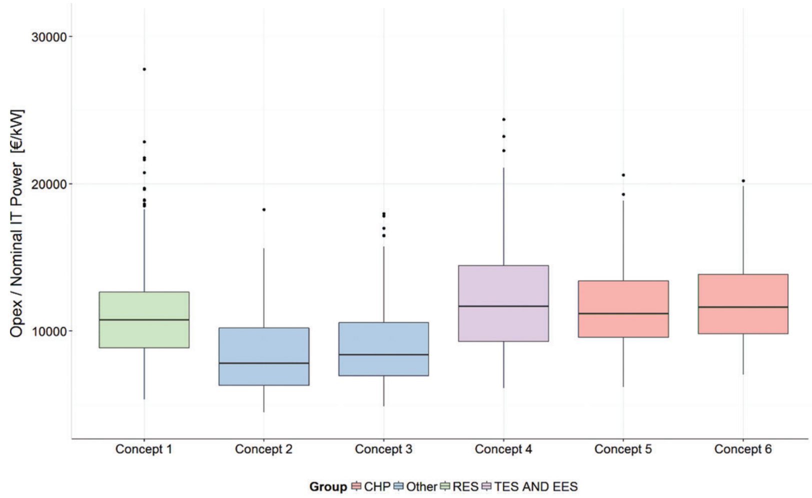


Figure 7.3 Evaluation of the concepts with respect to the OPEX/nominal IT power.

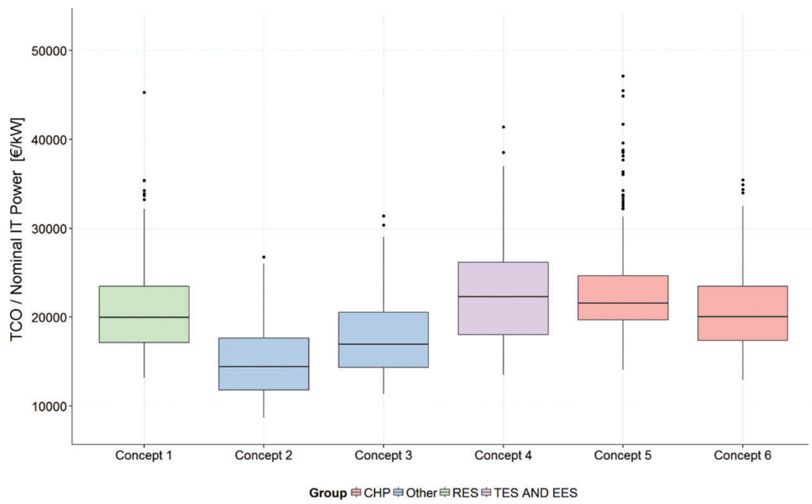


Figure 7.4 Evaluation of the concepts with respect to the TCO/nominal IT power.

even with a high renewable energy generation, has higher primary energy consumption than the concepts with the CHP system.

It can be seen in the Figure 7.2 that the investment cost of the systems (CAPEX) with a higher renewable energy generation (concepts 1 and 5) and with thermal and electrical storage (concept 4) is higher. The lowest investment cost is shown for concept 2, because district heating and cooling is

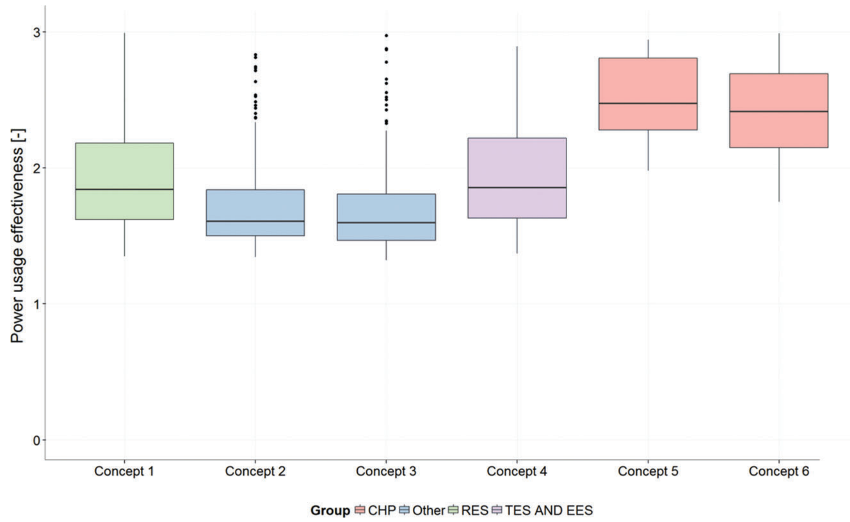


Figure 7.5 Evaluation of the concepts with respect to the PUE.

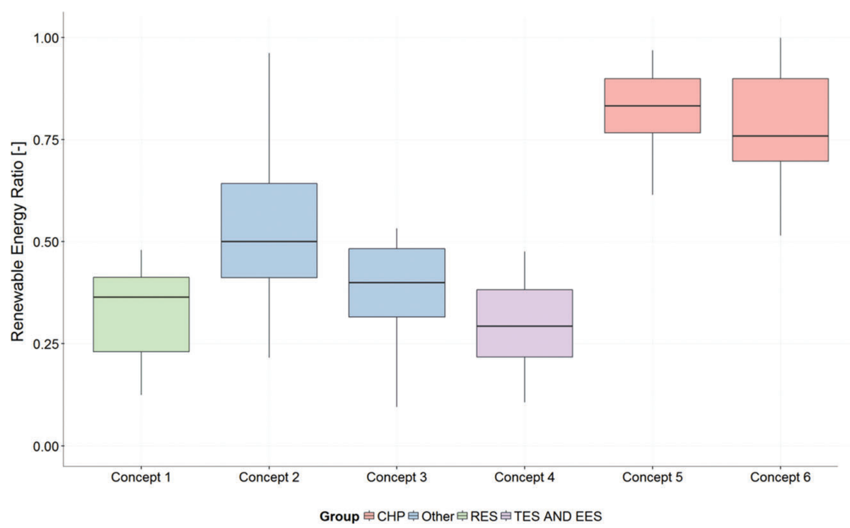


Figure 7.6 Evaluation of the concepts with respect to the RER.

an established technology and the Data Centre owner just pay for the connexion. Analysing the operational cost (Figure 7.3) of the systems (OPEX), concept 2 and 3 are the ones with lower cost of operation. On one hand, the cooling provided by the district cooling network is cheaper than the one generated onsite and on the other hand, the use of free cooling helps to reduce drastically the energy consumption for the cooling system. Concepts with CHP technologies have higher operational costs since they need biogas to run the engines and the fuel cells. With the addition of the operational cost (OPEX) to the capital cost (CAPEX), concept 2 followed by concept 3 are observed to be the better systems in term of the lowest global cost (TCO) per nominal IT power consumption (Figure 7.4).

Figure 7.5 shows the median value of the PUE for the different concepts. Note that for concepts with CHP systems (concepts 5 and 6) the median PUE is more than 2. This is because the rejected heat of the system is not counted in the PUE calculation, as the standardization bodies establish. Therefore, PUE metric for these systems does not capture the essence of such systems. In a Data Centre, excess heat could be from a CHP plant or from the IT white space. The re-used waste heat from IT is assumed to be 0 in the PUE calculation. On the other hand, the other concepts, especially concept 2 and 3 present median PUE values aligned with current trends. In order to make the Data Centre more energy efficient, an optimization process is needed for each specific concept and location.

Figure 7.6 illustrates the RER for the different concepts. Advanced solutions with the CHP system (concepts 5 and 6) have a higher RER, followed by the solution connected to the district cooling (concept 2).

7.2 Concept Comparison for Selected Scenarios

7.2.1 Description of Scenarios Analysed

The objective of this section is to study the energy and economic feasibility of different advanced concepts in three different locations (Barcelona, Stockholm and Frankfurt) under the same boundary conditions. It is considered a Data Centre with an IT power capacity of 1000 kW. The other main parameters such as the rack density, the occupancy ratio, the safety margin factor and the load profile are fixed as shown in Table 7.3. The safety margin factor is used to limit the maximum IT power capacity that the servers can run in the installation. As an example, a safety margin of 0.8 means that the maximum IT power consumption would be 80% of the total IT power capacity (1000 kW). The occupancy ratio means the ratio of installed IT, lack of occupancy is a lack of IT equipment. Therefore, for a Data Centre (power capacity of 1000 kW) with a safety margin of 0.8 and an occupancy ratio of 0.5, the maximum IT power consumption of the servers is 400 kW. The white space area basically

Table 7.3 Specific assumptions for the investigated concepts for a 1000 kW IT power Data Centre in three locations Barcelona (BCN), Stockholm (STO) and Frankfurt (FRA)

Parameter	Unit	BCN	STO	FRA
Location	[–]	Barcelona	Stockholm	Frankfurt
IT power capacity	[kW]	1000	1000	1000
Rack density	[kW/rack]	4	4	4
Occupancy ratio	[–]	1	1	1
Safety margin factor	[–]	0.8	0.8	0.8
White space area	[m^2]	750	750	750
IT Load profile	[–]	Mixed	Mixed	Mixed
Average electricity price	[€/kW·h_{el}]	0.0988	0.0630	0.0720
Biogas price	[€/kw·h_{biogas}]	0.08	0.08	0.08
District cooling price	[€/kW·h_{DCool}]	0.035	0.035	0.035
Exported heat price	[€/kW·h_{heat}]	0.025	0.025	0.025
Average ratio renewables in the grid	[–]	0.36	0.62	0.26
$w_{del,total,el}$ (average)	[–]	2.29	1.86	2.32
$w_{del,nren,el}$ (average)	[kW·h_{PE}/kW·h_{el}]	1.83	1.30	2.15
$w_{del,nren.biogas}$	[kW·h_{PE}/kW·h_{biogas}]	0.5	0.5	0.5
$w_{del,nren,DCool}$	[kW·h_{PE}/kW·h_{DCool}]	0.6	0.6	0.6
$w_{exp,nren,heat}$	[kW·h_{PE}/kW·h_{heat}]	0.7	0.7	0.7

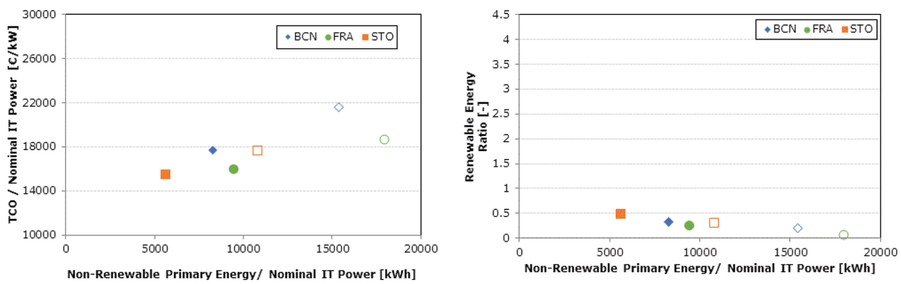
depends on the nominal IT power capacity (kW) and the rack density (kW per rack). The white space area was estimated using well-known industry average ratios for occupied floor occupied by a rack. The tables in section 3 show some of the basic parameters used to define the sizing of the main elements in the different energy concepts. In this analysis, the IT load profile used is a combination of the most standard IT workload profiles: Web, HPC and Data. In particular, the workload profile used is composed of 35% HPC, 30% Data and 35% Web based on Carbó et al. [5].

The simulation models developed allow the introduction of a set of energy efficiency measures individually or combined. The energy efficiency strategies are technical solutions that can be applied in almost all the Data Centres and combined with any system to supply cooling and power with or without renewable energy sources (RES). First, the strategies that allow reducing the load demand as much as possible have been integrated and analysed. Second, the use of RES has been studied. Energy efficiency measures can be grouped in the following categories:

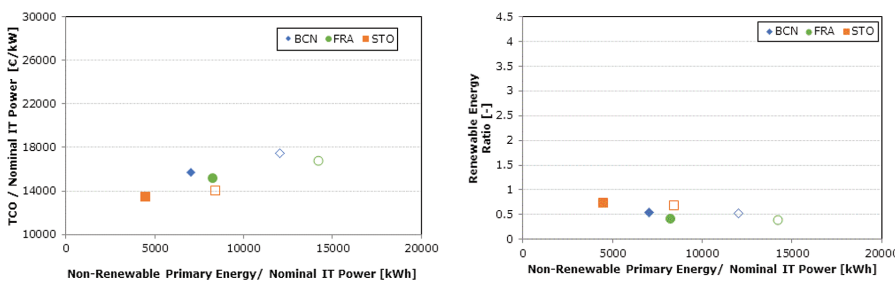
- Advanced measures for building design. The building design may affect the cooling demand of the Data Centre.
- Advanced measures for electrical supply. Some well-known strategies are modular UPS and bypassed UPS which achieve a reduction of electrical losses in the power distribution lines. In the results presented here, modular UPS have been applied when energy efficiency measures are mentioned.
- Advanced measures for cooling supply. These measures include the use of free cooling, hot/cold aisle containment for a better air management, variable air flow and the increase of allowable IT working temperatures. Using highly energy efficient components, in particular vapour compression chillers and CRAH units, can also lead to a significant reduction of the total energy demand.
- Advanced measures for IT management. Consolidation aims to concentrate IT workloads in a minimum number of servers to maintain the inactive servers in idle state. Then, those servers in idle state can be turned off. Finally, IT scheduling aims to move IT jobs according to the availability of RES when it is possible.

Figure 7.7 and Figure 7.8 present the results of the different advanced concepts proposed at the three different locations. In the same graph the results for each of the concepts applying the complete set of energy efficiency measures are presented and compared with the results of the reference case where none of these energy efficiency measures are implemented. In Figure 7.7 results in the graphs are grouped for each technical concept presenting normalized TCO and RER versus normalized primary energy consumption, respectively left and right. In Figure 7.8 the results are grouped for each location showing in the same graph the results for each concept.

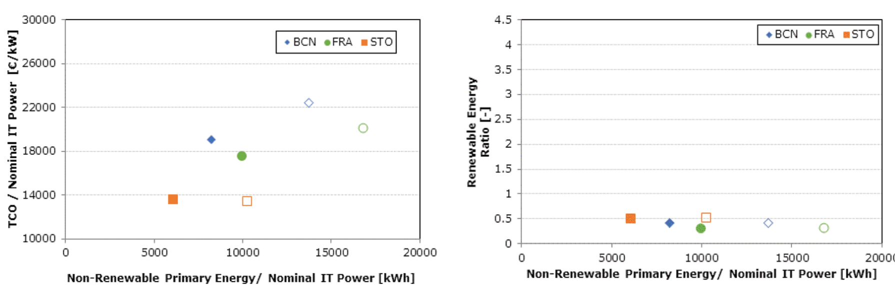
Talking about costs, one can observe that for the same concepts and the same sizes there are significant differences between operating a Data Centre in Barcelona, in Frankfurt or in Stockholm under the hypothesis used in this study. TCO costs are mainly driven by the sizes of the main elements and labour costs of building a Data Centre to determine the CAPEX (which is not influenced by the location since average European prices have been used) and for the energy prices that influence the OPEX (which differences come from the differences in the electricity prices). The average difference of TCO between having a Data Centre in Frankfurt compared to Barcelona is 7% and 24% if Stockholm is compared with Barcelona, Barcelona the location with the highest TCO. This is mainly due to the fact that the electricity price is higher in Barcelona than in Stockholm, while for Frankfurt an intermediate value is reached. As expected, these differences in TCO are reduced in the concepts where less electricity is needed to run the facility, like concept 5 and concept 6 where biogas is used to provide power/cold. In that case, it is still expensive to build and operate a Data Centre in Barcelona but only 3% more expensive compared to Frankfurt and 6% compared to Stockholm. The results present significant differences in the absolute values of PE_{nren} between the three locations. As PE_{nren} considers the amount of non-renewable primary



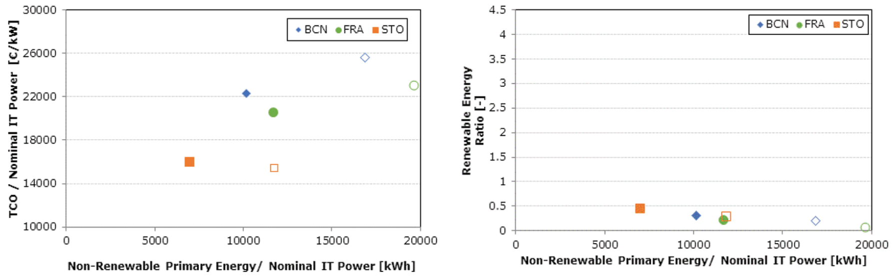
(a) Concept 1. Photovoltaic System and Wind Turbines with Vapour-Compression Chiller and Lead-Acid Batteries.



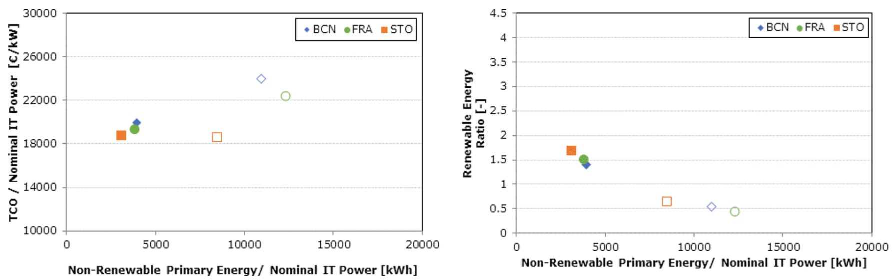
(b) Concept 2. District Cooling and Heat Reuse.



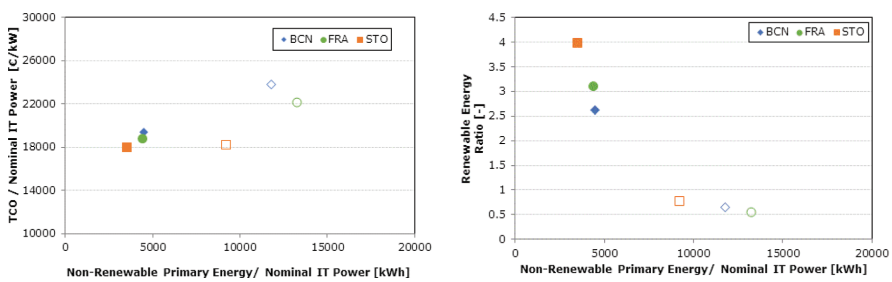
(c) Concept 3. Grid-Fed Wet Cooling Tower Without Chiller.



(d) Concept 4. Grid-Fed Vapour-Compression Chiller with Electrical Energy and Chilled Water Storages.



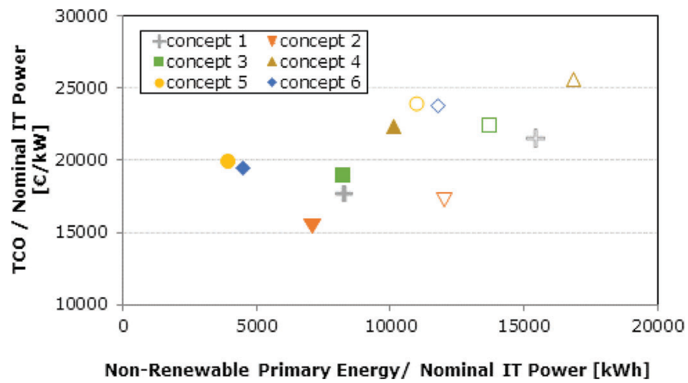
(e) Concept 5. Biogas Fuel Cell with Absorption Chiller.



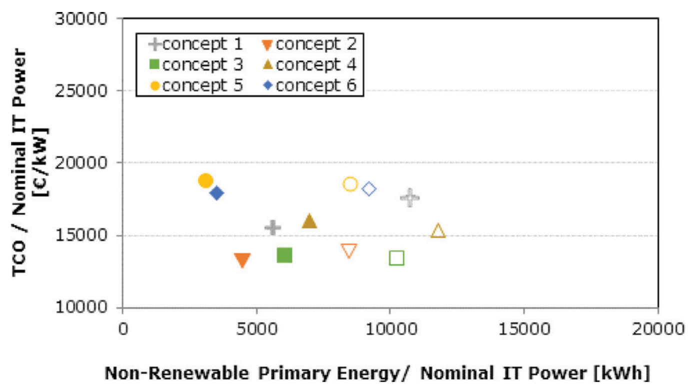
(f) Concept 6. Reciprocating Engine CHP with Absorption Chiller.

Figure 7.7 Normalized TCO vs. normalized PE_{nren} (left) and RER (RER) vs. normalized PE_{nren} (right) for each advanced technical concepts in three different locations (Barcelona, Stockholm and Frankfurt). Results of not applying energy efficiency measures (unfilled shapes) and applying energy efficiency measures (filled shapes) are shown for all the concepts.

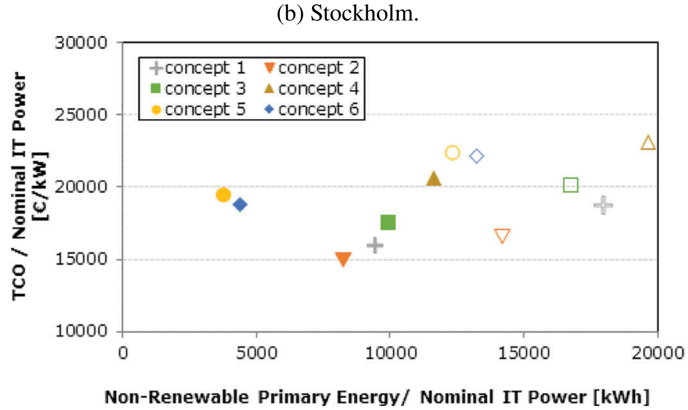
energy in the electricity network through the appropriate weighting factors, there is a difference between the locations as well as the influence of other climatic conditions: for example there are more hours of free cooling available in Stockholm than in Barcelona. Table 7.4 shows the results for concept 1



(a) Barcelona.



(b) Stockholm.



(c) Frankfurt.

Figure 7.8 Normalized TCO vs. normalized PE_{nren} for the location of (a) Barcelona, (b) Stockholm and (c) Frankfurt. Results of not applying energy efficiency measures (unfilled shapes) and applying energy efficiency measures (filled shapes) are shown for all the concepts.

Table 7.4 Normalized PE_{nren} consumption for concepts 1 and 5 for the locations of Barcelona, Frankfurt and Stockholm

	BCN	FRA	STO
Concept 1-Convectional DC with VCCH			
Without energy efficiency measures	15 403	17 924	10 776
With energy efficiency measures	8 286	9 419	5 608
Concept 5-Biogas Fuel Cells + Absorption chiller			
Without energy efficiency measures	10 962	12 287	8 478
With energy efficiency measures	3 934	3 786	3 099

and concept 5, where differences between locations in normalized PE_{nren} are reduced because concept 5 is mainly based on biogas which has the same conversion factor for the two locations.

For all the cases analysed, there is a significant benefit of applying as much energy efficiency measures as possible which will produce savings in the total costs and in the primary energy consumption. IT management strategies are the most beneficial ones, together with some measures which allow increasing the total number of free-cooling hours or improving the efficiency in the electrical distribution. For the case studies presented here, the impact of applying energy efficiency measures is a reduction in PE_{nren} up to 48% in Barcelona and 50% in Frankfurt and Stockholm as well as a reduction of TCO up to 15% in Barcelona and 13% in Frankfurt and Stockholm.

According to the results, operating a conventional Data Centre without renewables (concept 1) can cost between 17688 and 21613 €/kW_{IT} and consuming about 15403 $kW{\cdot}h_{PE,nren}/kW_{IT}{\cdot}year$ in Barcelona, 17924 $kW{\cdot}h_{PE,nren}/kW_{IT}{\cdot}year$ in Frankfurt and 10776 $kW{\cdot}h_{PE,nren}/kW_{IT}{\cdot}year$ in Stockholm. Although, it was commented that a significant reduction of TCO and PE_{nren} is possible applying different energy efficiency strategies, a reduction of primary energy resources is possible with different concepts to run a Data Centre. Among the ones detailed described in Chapter Six, concept 5 based on biogas fuel-cells gives the best results in terms of PE_{nren} reduction although it is an expensive concept compared to a conventional Data Centre (concept 1). Having a CHP with a biogas engine (concept 6) gives also promising PE_{nren} savings but is less expensive than concept 5 although still having a higher TCO than a conventional Data Centre. Both concepts 5 and 6 rely also on the availability of biogas as local and/or imported resource and the excess of heat produced by the fuel cells or the CHP system is 100% reused. The most cost effective concept, i.e. the one that combines more

PE_{nren} and TCO savings, is concept 2 which connects the Data Centre to a district cooling system and heat from the Data Centre can be used for heating purposes. The reduction of TCO can reach up to 21% and the PE savings up to 22% when no energy efficiency measures are applied. Concepts 2, 5 and 6 rely on a 100% reuse of the heat produced by the facility. The implementation of concept 3 based on wet cooling towers shows moderate PE savings compared to conventional concept and even no benefit in location where free-cooling strategies can be applied. Concept 4 is the one that shows higher costs and higher primary energy consumption in all of the locations. Higher costs come from the additional storage systems which do not produce enough savings in energy costs to compensate the additional investment. Also, an increase of primary energy consumption is shown. These results related to concept 4 indicate that it is an advanced technical concept which may have some benefits in specific contexts where high fluctuation of energy prices (or share of renewables in the grid) occurs along the day.

7.3 Detailed Analysis by Advanced Technical Concepts

7.3.1 Introduction

In this section, a detailed analysis studying the implementation of energy efficiency measures and varying some main parameters such as the IT power and the size of the elements of the system is presented. The reference system (vapour compression system with CRAH units) is a Data Centre with an IT power capacity of 1000 kW located in two different locations: Barcelona and Stockholm. The main parameters of the installation are shown in Table 7.3. To analyse the influence of the 14 energy efficiency measures accumulative tests (sequential and accumulative implementation of each strategy) have been followed for all the scenarios. The accumulative effect helps to assess the relative influence of the measures and to quantify the optimization. Table 7.5 shows the values used for all the parameters affecting each of the energy efficiency strategy implementation for the accumulative tests.

7.3.2 Concept 1. Photovoltaic System and Wind Turbines with Vapour-Compression Chiller

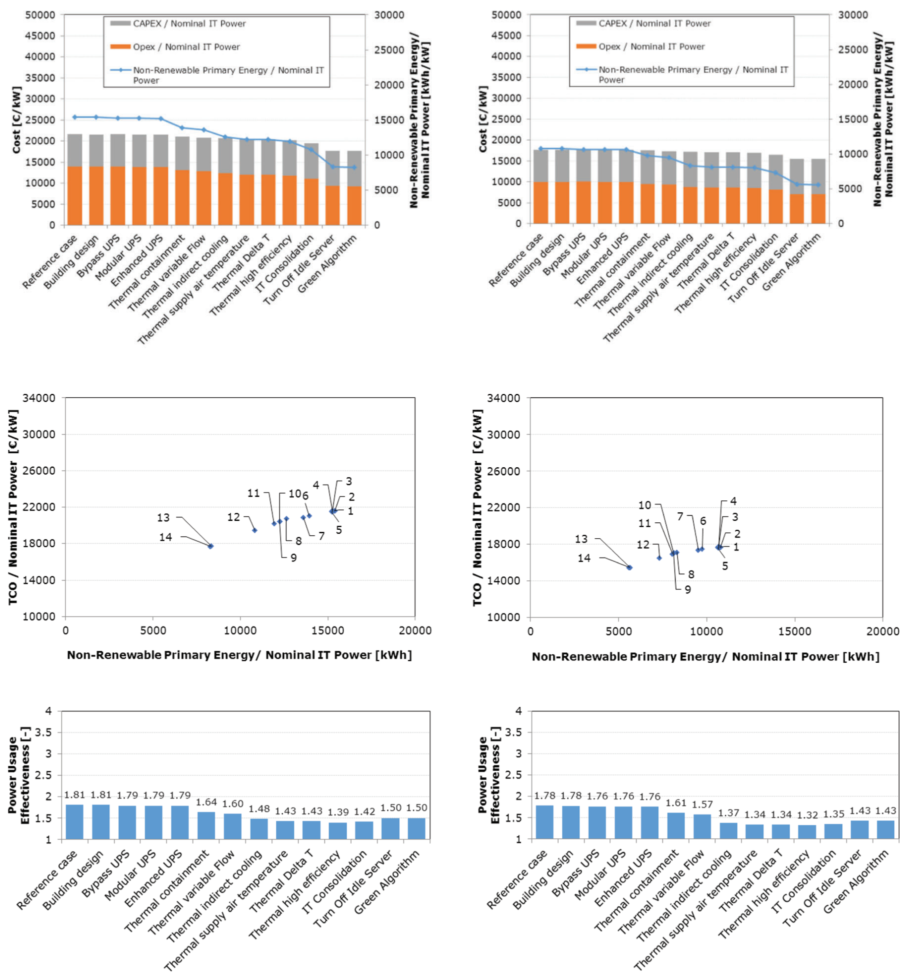
7.3.2.1 Influence of energy efficiency measures

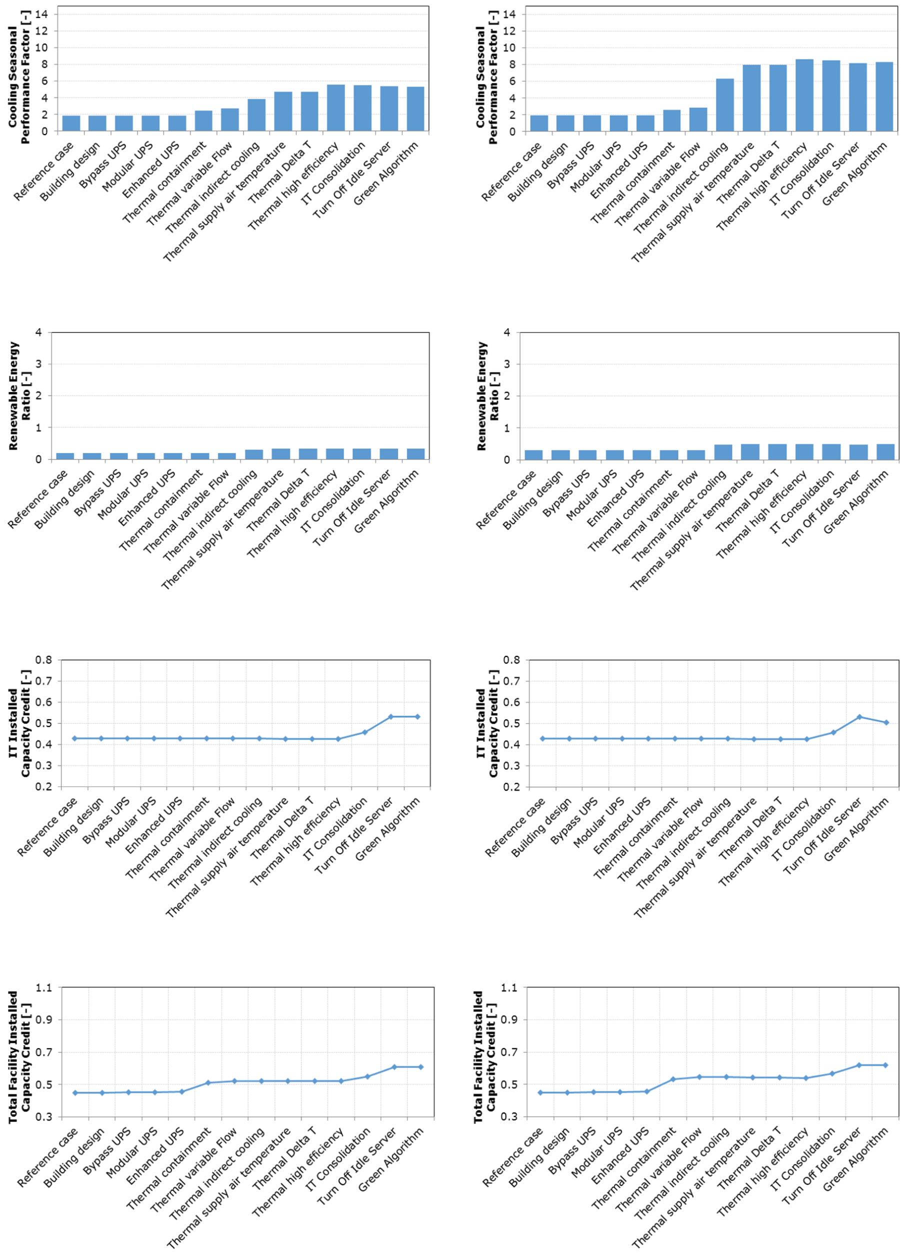
The results of the accumulative tests are presented in two ways: results for each metric analysed (Figure 7.9) and the sizes of the main elements (Table 7.6).

Table 7.5 Energy efficiency strategies and their values for the accumulation test

Variable Parameter	Unit	01_Reference Case	02_Building Design	03_Bypass UPS	04_Modular UPS	05_Enhanced UPS	06_Thermal Containment	07_Thermal Variable Flow	08_Thermal Indirect Cooling	09_Thermal SupplyAir Temperature	10_Thermal Delta T	11_Thermal High Efficiency	12_ IT Consolidation	13_TurnOffIdleServer	14_Green Algorithm
WSP thermal transmissivity	[kJ/ hr·m^2· K]	1.8	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12	6.12
UPS operation mode	[–]	0	0	2	1	1	1	1	1	1	1	1	1	1	1
UPSoversized power converter	[–]	0	0	0	0	1	1	1	1	1	1	1	1	1	1
WSP air containment	[–]	0	0	0	0	0	1	1	1	1	1	1	1	1	1
Variable flow rate	[–]	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Max. Ambient temp. IAFC	[°C]	–100	–100	–100	–100	–100	–100	–100	AHU_ Tsupply-5	AHU_ Tsupply-5	AHU_ Tsupply-5	AHU_ Tsupply-5	AHU_ Tsupply-5	AHU_ Tsupply-5	AHU_ Tsupply-5
WSP supply temp.	[°C]	20	20	20	20	20	20	20	20	24	24	24	24	24	24
Air temp. increase in WSP	[K]	7	7	7	7	7	7	7	7	7	15	15	15	15	15
VCCH nominal COP	[–]	4	4	4	4	4	4	4	4	4	4	5.5	5.5	5.5	5.5
Virtualization technique	[–]	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Turn off idle server	[–]	0	0	0	0	0	0	0	0	0	0	0	0	1	1
IT scheduling	[–]	0	0	0	0	0	0	0	0	0	0	0	0	0	1

The non-renewable primary energy is influenced mainly by thermal containment, thermal indirect cooling, IT consolidation and turn off idle server. These measures lead to a significant decrease (46% for Barcelona and 48% for Stockholm) of the metric values. Due to a decreasing OPEX (33% for Barcelona and 30% for Stockholm) and slightly increasing CAPEX (9% for Barcelona and Stockholm) with the application of the measures the TCO shows a slight decrease of about 18% for Barcelona and 12% for Stockholm as well. The results of the PUE in both locations show the most significant decrease (22% for Barcelona and 26% for Stockholm) due to the





a) b)

Figure 7.9 Results of accumulative tests for concept 1 in a) Barcelona and in b) Stockholm.

Table 7.6 Accumulation test results for the size of the main elements in concept 1

Components	Unit	Case 1	2	3	4	5	6	7	8	9	10	11	12	13	14
VCCh chiller (nominal power)	kW	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Dry cooler (nominal power)	kW	1875	1875	1875	1875	1875	1875	1875	1875	1875	1875	1773	1773	1773	1773
Total air mass flow rate	t/h	768	768	768	768	768	302	302	302	302	302	302	302	302	302
Power consumption of fans	kW	94	94	94	94	94	37	37	37	37	37	37	37	37	37
Transformer (Nominal power)	kW	2169	2169	2169	2169	2169	2019	2019	2019	2019	2019	1879	1879	1879	1879
Switchgear (Nominal current of)	kW	4139	4139	4139	4139	4139	3853	3853	3853	3853	3853	3587	3587	3587	3587
Generator (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Uninterruptible Power Supply unit (Nominal power)	kW	629	629	629	629	629	629	629	629	629	629	629	629	629	629
Power Distribution unit (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500

use of thermal containment, thermal variable flow, thermal indirect cooling and the increase of supply air temperature. However a marginal increase of the metric value due to IT consolidation and turn off idle server is reached. The most noticeable increase (6% for Barcelona and 78% for Stockholm) of the cooling seasonal performance factor with the application of the efficiency measures can be found for thermal containment, thermal variable flow, thermal indirect cooling, the increase of supply air temperature and the use of high efficiency thermal elements whereas the application of IT consolidation and turn off idle servers lead to a slight decrease of the metric. This behaviour is valid for Barcelona and Stockholm as well. The RER increases significantly (39% for Barcelona and Stockholm) mainly due to the application of thermal indirect cooling for both locations equally. The IT installed capacity credit shows an independent behaviour towards the applied measures except for IT consolidation and turn off idle server. They lead to a significant increase (19% for Barcelona) of the metric values. This behaviour is equal for the two locations whereas for Stockholm the use of green algorithm leads to slightly decreasing values. Compared to the IT installed capacity credit, the total facility installed capacity credit shows similar dependencies but additionally presents increasing values with the use of thermal containment.

When analysing the sizes of the main elements the nominal power of the dry cooler, the total air mass flow rate, the power consumption of the fans, the nominal power of the transformer and the nominal current of the switchgear show a dependency on single applications of the efficiency measures. While the use of thermal containment leads to a reduction of the total air mass flow rate, the power consumption of the fans, the nominal power of the transformer and the nominal current of the switchgear the nominal power of the dry cooler is not affected. Also the application of high efficiency thermal elements components leads to decreasing values of the nominal power of the dry cooler, the nominal power of the transformer and the nominal current of the switchgear.

7.3.2.2 Influence of size

The variation of the Data Centre nominal IT power shown in Figure 7.10 is evaluated for the TCO and the RER in two locations Barcelona and Stockholm. Regarding the costs it can be analysed that the decrease with the application of all energy efficiency measures is more distinctly for Barcelona (15–20%) then for Stockholm (10–15%), however, the absolute cost values for Barcelona are 10–20% higher. The decrease of the non-renewable primary energy values with the application of the efficiency measures shows a similar tendency.

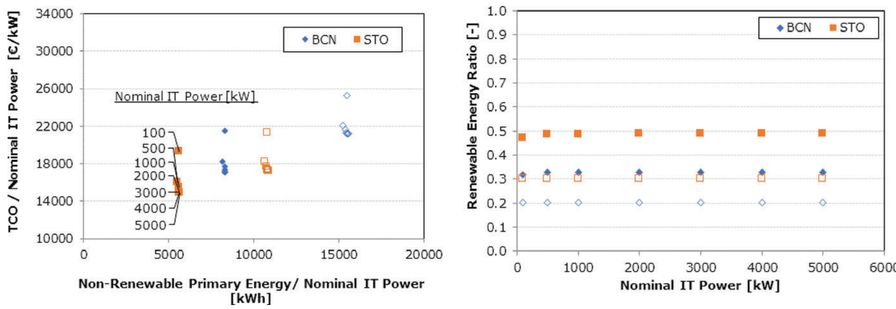


Figure 7.10 Variation of the Data Centre nominal IT power for the two locations (Barcelona and Stockholm) for concept 1. Unfilled shapes represent the reference case and filled shapes the case with all energy efficiency measures applied.

However, the decrease of about 47–48% is equal for both locations, whereas the absolute value is 30–32% higher for Barcelona than for Stockholm. The dependency of the nominal IT power is comparable for both locations and lead to decreasing costs of maximal 21% for Barcelona and 23% for Stockholm while the influence on the non-renewable primary energy is insignificant. The highest decrease of the costs can be analysed from 100 kW to 500 kW with a maximum cost reduction of 15% compared to the next variation steps (500, 1000, 2000 etc.) with a maximal decrease of 2%. Regarding the RER, the application of energy efficiency measures leads to a significant increase of maximal 39% for both locations. IT can be concluded that the location and neither the size of the Data Centre show a major dependency on this metric.

7.3.2.3 On-Site renewable energy systems implementation

Figure 7.11 depicts graphically the results of applying on-site renewable power systems to a conventional Data Centre: PV and wind turbines systems. On one hand, different sizes of on-site PV systems, which are characterized by their PV peak power, have been simulated. For the scenarios of 120 kW_{IT} and 400 kW_{IT}, PV systems are varied from 0 to 50 kWp and from 0 to 100 kWp, respectively (see Table 7.7). PV simulation which is integrated as part of the overall TRNSYS Data Centre models neglects the shadows effects of surrounding buildings and the own shadows of a large flat roof mounted PV field. The PV field is considered oriented south with an inclination slope of 32.2º for Barcelona and 44.6º for Stockholm. On the other hand, the use of

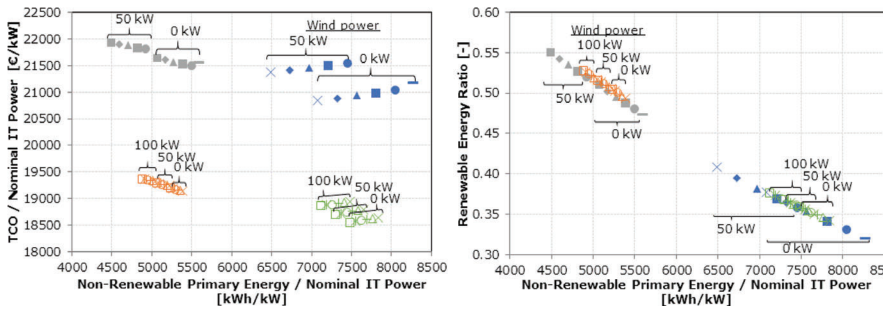


Figure 7.11 Normalized TCO (left) and RER (right) vs. normalized PE_{nren} for different scenarios when adding on-site renewable power systems to concept 1.

Table 7.7 Specific assumptions of on-site PV and wind power systems for the investigated concept 1

Parameter	Unit	BCN-120/STO-120	BCN-400/STO-400
Total PV peak power	[kWp]	0, 10, 20, 30, 40, 50	50, 60, 70, 80, 90, 100
Total Wind rated power	[kW]	0, 50	0, 50, 100

small wind power systems has also been studied. For the 120 kW_{IT} Data Centre a unique 50 kW rated power wind turbine (Aeolos, 2015) is considered; while, for the 400 kW_{IT} Data Centre, the impact of having one and two identical wind turbines has been calculated.

As expected, adding on-site PV and wind power systems implies an increase of the RER, as well as a decrease of the PE_{nren}. However, when analysing the economic and the energetic impact, the location of the Data Centre has a big influence. It is shown that on-site PV systems are cost-effective when they are implemented in Data Centres located in Barcelona (south Europe) under the hypothesis of this study but the installation of PV systems in Stockholm are not cost-effective due to investment, the electricity prices considered and the low solar radiation over the year. Renewable electricity produced by on-site wind power systems in Barcelona and in Stockholm, which is based on wind availability in Meteonorm data files [5], is not enough to compensate the investment needed for such a systems. Using on-site wind power systems needs to be installed in locations where wind resource is available, which strongly depends on local conditions. Table 7.8 shows the required roof space for a 50 kWp and 100 kWp PV field under the hypothesis that the PV field is mounted in a flat roof by tilted modules with a distance between rows based on rules which optimally minimize the occupancy of the

Table 7.8 Required roof space, available roof space and load cover factor for different scenarios with on-site PV power system for the investigated concept 1

		Name of the Scenarios			
Parameter	Unit	BCN-120	BCN-400	STO-120	STO-400
Required roof space – 50 kWp	[m^2]	796		1570	
Required roof space – 100 kWp	[m^2]	1593		3140	
Available roof space	[m^2]	198	660	198	660
Load cover factor – 50 KWp	[%]	16	5	10	3
Load cover factor – 100 KWp	[%]	–	9	–	6

roof and maximizes the PV production [6]. The required roof space depends on the size of the PV system and on the location. Although different types of Data Centre buildings exist and whitespace rooms can be part of large corporate buildings, available roof space (A_{roof}) is estimated in relation with the white space area ($A_{DC,room}$) as shown in Equation (7.1) and based on information available from the industry. In some cases, to cover the expected PV peak power, The required roof space for the PV field exceeds the available space. Results of the load cover factor, which represents the ratio between the power produced by PV and the overall electrical Data Centre consumption, are also presented in Table 7.8 The load cover factor is very low (less or equal to 10% in most of the cases) even with PV systems that go beyond the available roof space. This means, that under grid parity conditions having an on-site PV system is a good solution to reduce the environmental impact of a Data Centre. Although this will be very dependent on the case, conventional roof mounted PV fields are limited by the available roof space covering a small portion of the electricity consumption of a Data Centre. Using PV to have larger load cover factors would require to use additional space available in the Data Centre footprint or explore building integrated PV solutions.

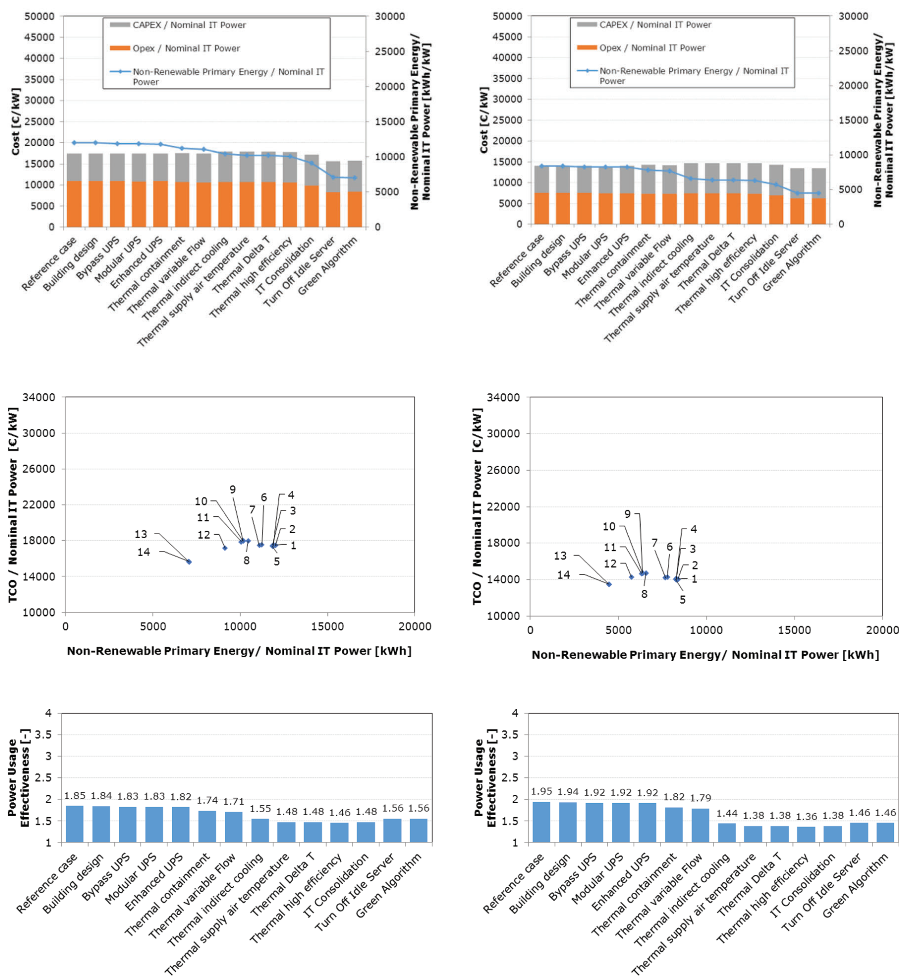
$$A_{roof} = f_{roof-ws} \cdot A_{DC,room};$$
$$\text{where } f_{roof-ws} \cdot = 2.2 m^2_{roof}/m^2_{DC,room} \tag{7.1}$$

7.3.3 Concept 2. District Cooling and Heat Reuse

7.3.3.1 Influence of energy efficiency measures

For concept 2 the results of the accumulative tests are presented in Figure 7.12 (results for each metric analysed) and Table 7.9 (sizes of the main elements).

The energy efficiency measures influencing the results of the non-renewable primary energy are thermal containment, thermal indirect cooling, IT consolidation and turn off idle server. They lead to a significant decrease (42% for Barcelona and 47% for Stockholm) of the metric values. A decreasing OPEX (23% for Barcelona and 18% for Stockholm) and slightly increasing CAPEX (11% for Barcelona and Stockholm) with the application of all measures cause a slight decrease of the TCO of about 10% for Barcelona and 4% for Stockholm. The most significant decrease of 21% for Barcelona



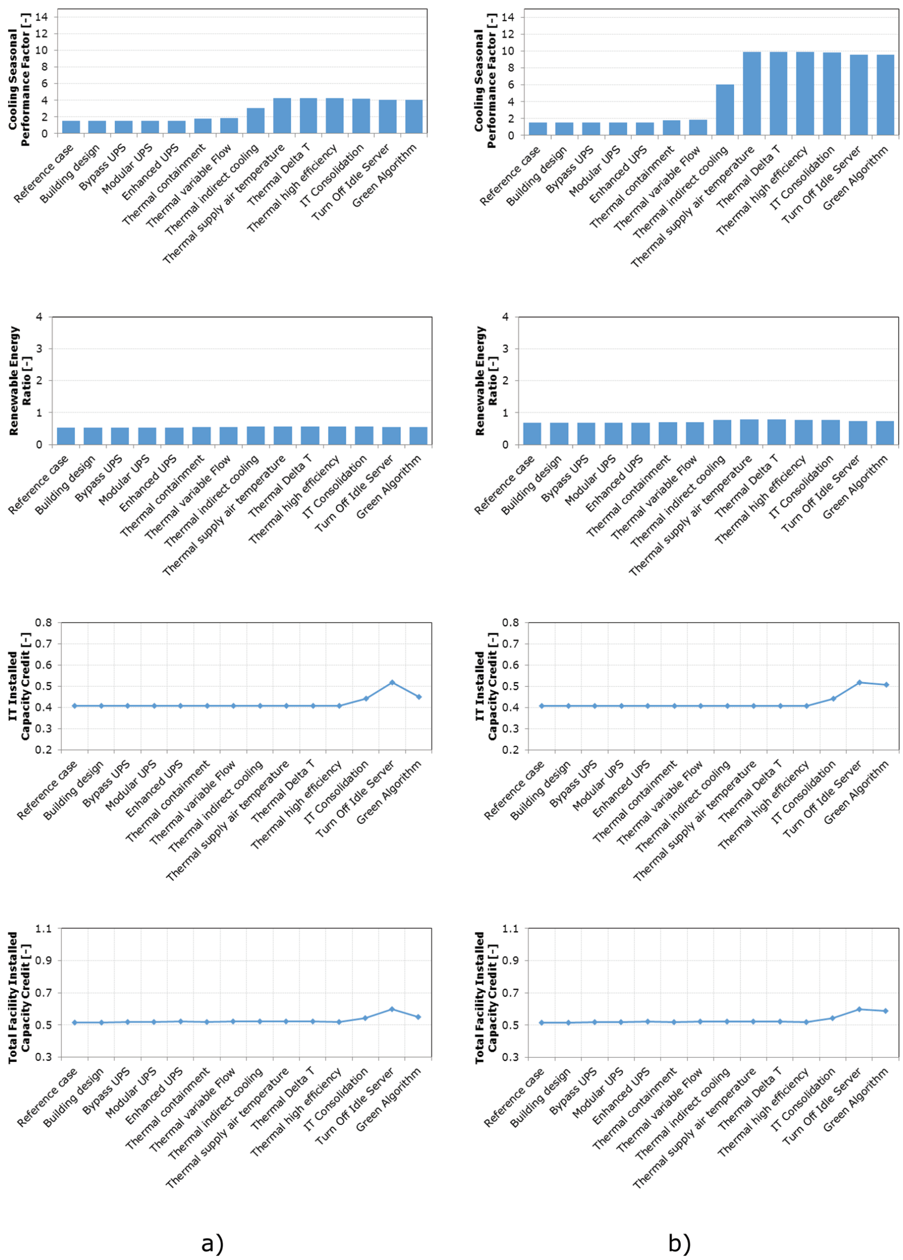


Figure 7.12 Results of accumulative tests for concept 2 in a) Barcelona and in b) Stockholm.

Table 7.9 Accumulation test results for the size of the main elements in concept 2

Components	Unit	Case													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Heat pump (heating capacity)	kW	175	175	175	175	175	175	175	175	175	175	175	175	175	175
Total air mass flow rate	t/h	544	544	544	544	544	214	214	214	214	214	214	214	214	214
Power consumption of fans	kW	67	67	67	67	67	26	26	26	26	26	26	26	26	26
Transformer (TR) (Nominal power)	kW	1758	1758	1758	1758	1758	1651	1651	1651	1651	1651	1589	1589	1589	1589
Switchgear (SWG) (Nominal current of)	kW	3354	3354	3354	3354	3354	3151	3151	3151	3151	3151	3033	3033	3033	3033
Generator (GE) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Uninterruptible Power Supply unit (UPS) (Nominal power)	kW	629	629	629	629	629	629	629	629	629	629	629	629	629	629
Power Distribution unit (PDU) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500

and 30% for Stockholm of the PUE can be found due to the use of thermal containment, thermal variable flow, thermal indirect cooling, the increase of supply air temperature and the use of high efficiency thermal elements. However, a slight increase of the metric value due to IT consolidation and turn off idle server is reached. The cooling seasonal performance factor increases significantly (65% for Barcelona) with the application of the efficiency measures such as thermal containment, thermal variable flow, thermal indirect cooling and the increase of supply air temperature whereas the application of IT consolidation and turn off idle server lead to a slight decrease of the metric. This behaviour is valid for the two locations equally. However, for Stockholm the increase of 85% of the cooling seasonal performance factor is mainly due to the efficiency measure thermal indirect cooling and the increase of supply air temperature. Regarding the RER an increase of 9% for Barcelona and 13% for Stockholm is mainly caused due to the application of thermal indirect cooling and the increase of supply air temperature, while IT consolidation and turn off idle server lead to an insignificant decrease. The IT installed capacity credit shows no dependency towards the applied measures except for IT consolidation, turn off idle server and green algorithm. While the first two measures lead to a significant increase of 23% for Barcelona and for Stockholm the use of green algorithm leads to decreasing values for Barcelona (13%) and Stockholm (4%) as well. Compared to the IT installed capacity credit, the total facility installed capacity credit shows similar dependencies just in a less distinctive way.

When analysing the sizes of the main elements the total air mass flow rate, the power consumption of the fans, the nominal power of the transformer and the nominal current of the switchgear show a dependency on single applications of the efficiency measures. These are comparable to the analysis done for concept 1 (see Subsection 7.3.2.1).

7.3.3.2 Influence of size

The variation of the Data Centre nominal IT power shown in Figure 7.13 is evaluated for the TCO and the RER. Analyzing the effects in costs of the energy efficiency strategies implementation, it is seen that locations such as Barcelona (8–12%) is more influenced by this than Stockholm (2–5%). However, the absolute cost values for Barcelona are 12–20% higher. Regarding the non-renewable primary energy values a decrease of 42% can be reached for Barcelona and 47% for Stockholm. The dependency of the nominal IT power is comparable for both locations and leads to decreasing costs up to 18% for Barcelona and 20% for Stockholm while the influence on the non-renewable

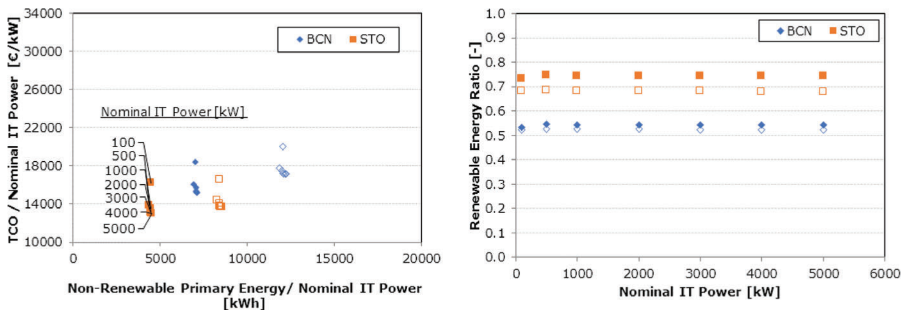


Figure 7.13 Variation of the Data Centre nominal IT power for the two locations (Barcelona and Stockholm) for concept 2. Unfilled shapes represent the reference case and filled shapes the case with all energy efficiency measures applied.

primary energy is insignificant. The most notable decrease of the costs can be seen from 100 kW to 500 kW with a maximum cost reduction of 14% compared to the next variation steps (500 kW, 1000 kW, 2000 kW, etc.) with a maximum decrease of 3%. Regarding the RER, the application of energy efficiency measures lead to a significant increase up to 4% for Barcelona and 8% for Stockholm. The size of the Data Centre does not show a major dependency of this metric.

7.3.3.3 Influence of the liquid cooling solution and the potential heat reuse

Figure 7.14 presents the results of the parametric analysis for concept 2 (Data Centre connected to a district cooling and heating system with reuse of heat from direct liquid cooled servers) for Data Centres of 400 kW_{IT} in both locations (Barcelona-400 and Stockholm-400). Only results for 400 kW_{IT} are presented to contribute to readability of the graphs. Maintaining the hypothesis that 100% of the heat extracted from the Data Centre can be reused, the sensitivity analysis for two parameters has been performed. On one hand, there is the type of liquid cooling system which is characterized by its efficiency: 0.65 for on-chip liquid cooling and 1.0≃0.99 for immersed liquid cooling system. This parameter means that for on-chip liquid cooling, 65% of the heat is extracted by water and the other 35% by air, while for immersed liquid cooling systems, 100% of the heat is extracted by water. On the other hand, the size of the heat pump is varied which is characterized by the ratio between the heat pump cooling power and the maximum liquid cooling demand of the Data Centre. This ratio is varied from 0.1 to 0.5. The results

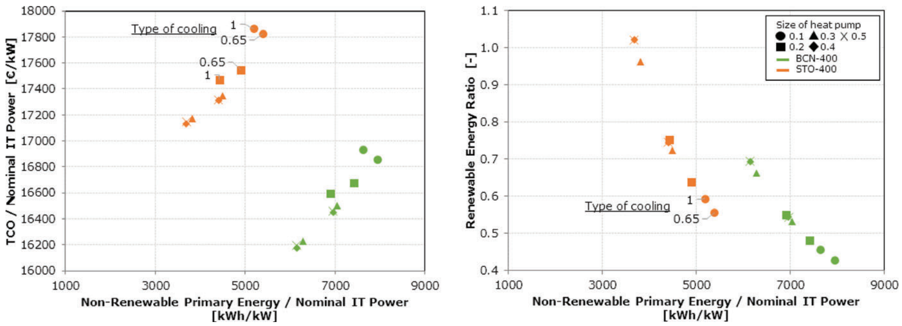


Figure 7.14 Normalized TCO (left) and RER (right) vs. normalized PE_{nren} for different scenarios, types of cooling (On-chip/Immersed) and sizes of the absorption chiller for concept 2.

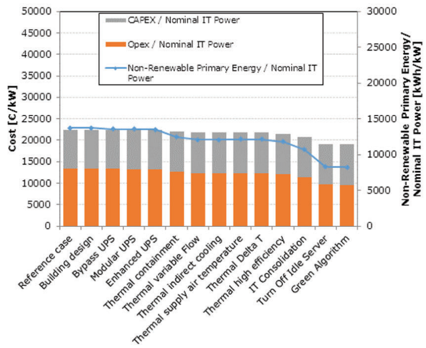
show that as the type of liquid cooling system allows extracting higher amount of heat from the servers, PE_{nren} decreases as well as RER increases. As the ratio determining the size of the heat pump increases there is a reduction of the PE_{nren}, too. Having an immersed liquid cooling system with the capability to extract more heat is a bit more expensive, but with optimum sizes of the heat pump differences between liquid cooling technologies are minimized in terms of TCO and PE_{nren}. As it is shown in Figure 7.14, the size of the heat pump has an important effect on the indicators having an optimal value between 0.4 and 0.5, while the differences between these two values of the parameter are negligible.

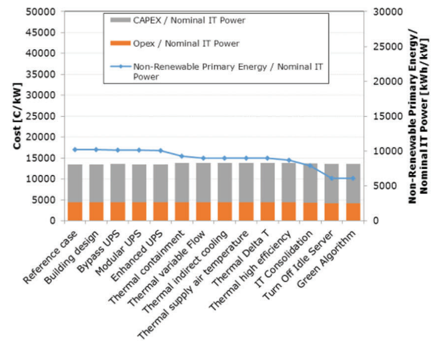
7.3.4 Concept 3. Grid-Fed Wet Cooling Tower without Chiller

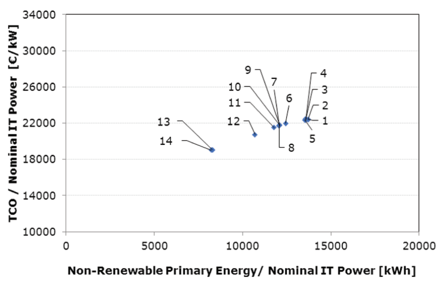
7.3.4.1 Influence of energy efficiency measures

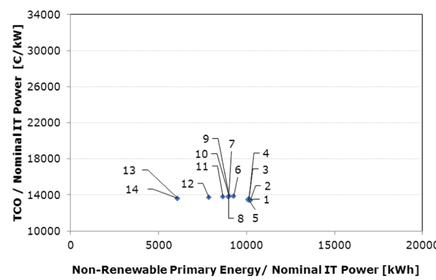
The results of the accumulative tests for concept 3 are presented in Figure 7.15 (results for each metric analysed) and Table 7.10 (the sizes of the main elements of each concept).

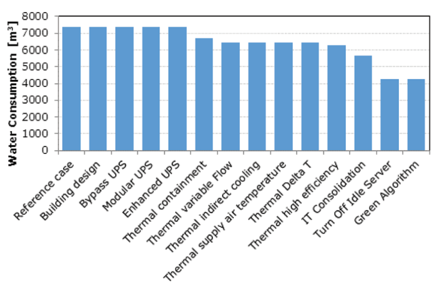
Concerning the non-renewable primary energy the highest dependency of the metrics can be analysed with the application of thermal containment, IT consolidation and turn off idle server in both locations. They lead to a significant decrease of 40% for Barcelona and Stockholm. The same efficiency measures lead to a decreasing OPEX (28% for Barcelona) and slightly increasing CAPEX (4% for Barcelona) which causes a slight decrease of

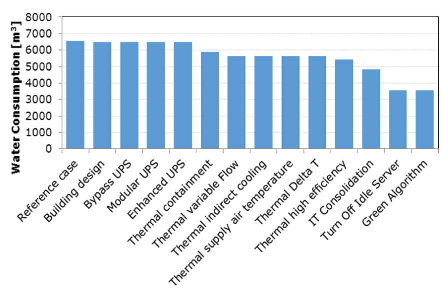

CAPEX / Nominal IT Power
Opex / Nominal IT Power
Non-Renewable Primary Energy / Nominal IT Power
Cost [€/kW]
Non-Renewable Primary Energy/ Nominal IT Power [kWh/kW]
Reference case
Building design
Bypass UPS
Modular UPS
Enhanced UPS
Thermal containment
Thermal variable Flow
Thermal indirect cooling
Thermal supply air temperature
Thermal Delta T
Thermal high efficiency
IT Consolidation
Turn Off Idle Server
Green Algorithm

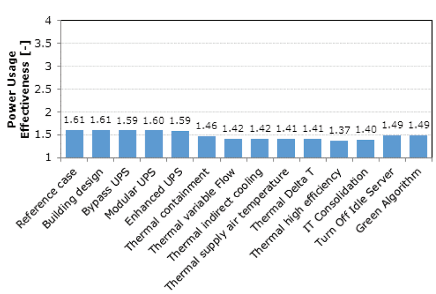

CAPEX / Nominal IT Power
Opex / Nominal IT Power
Non-Renewable Primary Energy / Nominal IT Power
Cost [€/kW]
Non-Renewable Primary Energy/ Nominal IT Power [kWh/kW]
Reference case
Building design
Bypass UPS
Modular UPS
Enhanced UPS
Thermal containment
Thermal variable Flow
Thermal indirect cooling
Thermal supply air temperature
Thermal Delta T
Thermal high efficiency
IT Consolidation
Turn Off Idle Server
Green Algorithm

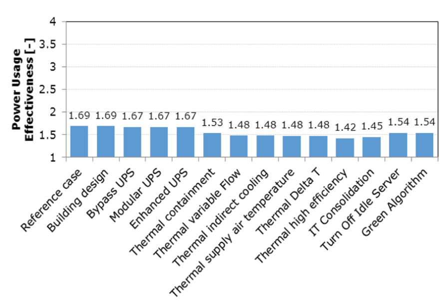

TCO / Nominal IT Power [€/kW]
Non-Renewable Primary Energy/ Nominal IT Power [kWh]


TCO / Nominal IT Power [€/kW]
Non-Renewable Primary Energy/ Nominal IT Power [kWh]


Water Consumption [m³]
Reference case
Building design
Bypass UPS
Modular UPS
Enhanced UPS
Thermal containment
Thermal variable Flow
Thermal indirect cooling
Thermal supply air temperature
Thermal Delta T
Thermal high efficiency
IT Consolidation
Turn Off Idle Server
Green Algorithm


Water Consumption [m³]
Reference case
Building design
Bypass UPS
Modular UPS
Enhanced UPS
Thermal containment
Thermal variable Flow
Thermal indirect cooling
Thermal supply air temperature
Thermal Delta T
Thermal high efficiency
IT Consolidation
Turn Off Idle Server
Green Algorithm


Power Usage Effectiveness [-]
1.61 1.61 1.59 1.60 1.59 1.46 1.42 1.42 1.41 1.41 1.37 1.40 1.49 1.49
Reference case
Building design
Bypass UPS
Modular UPS
Enhanced UPS
Thermal containment
Thermal variable Flow
Thermal indirect cooling
Thermal supply air temperature
Thermal Delta T
Thermal high efficiency
IT Consolidation
Turn Off Idle Server
Green Algorithm


Power Usage Effectiveness [-]
1.69 1.69 1.67 1.67 1.67 1.53 1.48 1.48 1.48 1.48 1.42 1.45 1.54 1.54
Reference case
Building design
Bypass UPS
Modular UPS
Enhanced UPS
Thermal containment
Thermal variable Flow
Thermal indirect cooling
Thermal supply air temperature
Thermal Delta T
Thermal high efficiency
IT Consolidation
Turn Off Idle Server
Green Algorithm

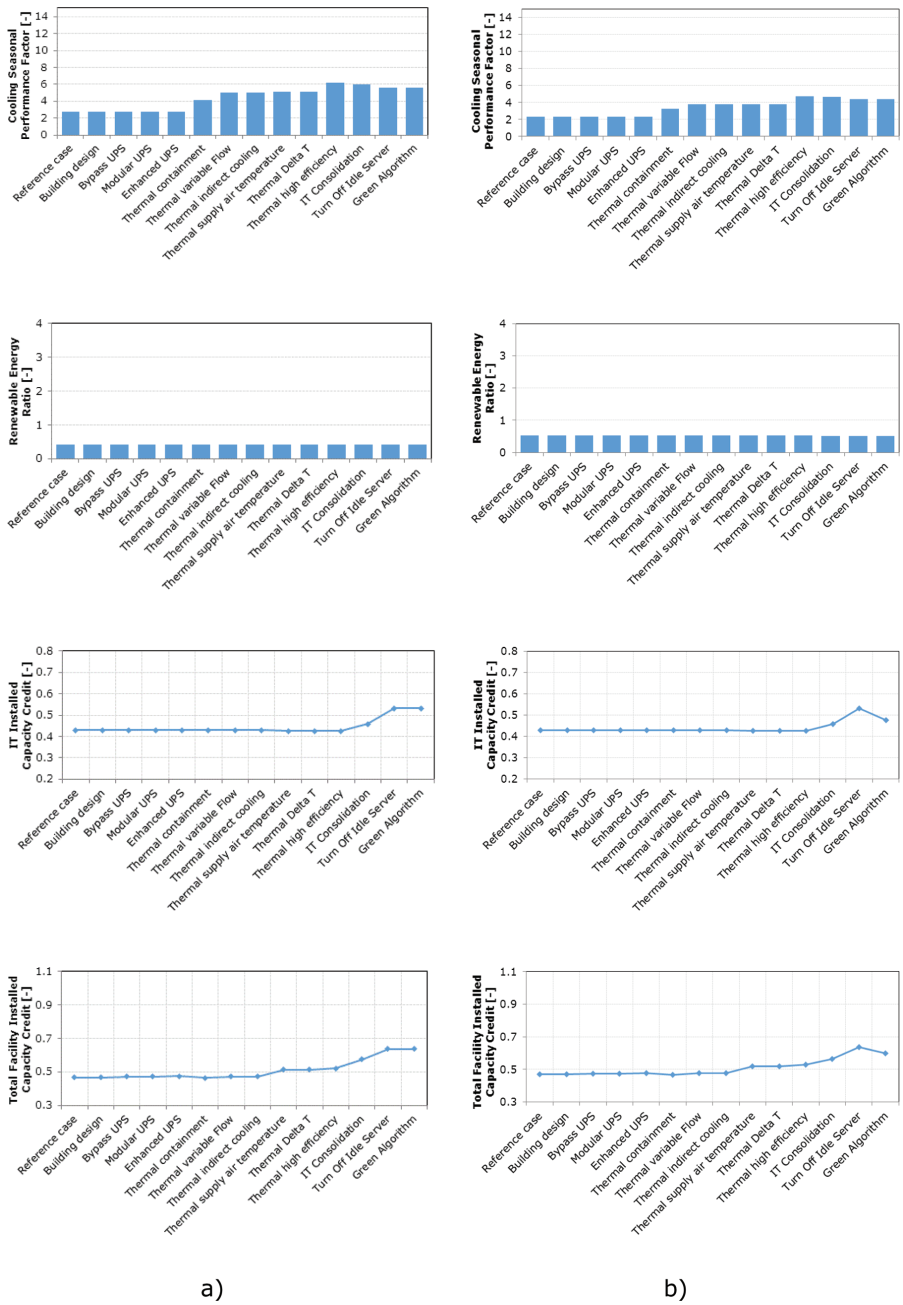


Figure 7.15 Results of accumulative tests for concept 3 in a) Barcelona and in b) Stockholm.

the TCO of about 15% for Barcelona as well. For the location Stockholm the increase of the CAPEX and the decrease of the OPEX compensate and lead to nearly constant TCO values. The water consumption is analysed due to the fact that in concept 3 a wet cooling tower is applied. Decreasing values of this metric can be observed due to the application of thermal containment and thermal variable flow as well as IT consolidation and turn off idle server. The overall reduction of the water consumption applying all energy efficiency measures reached up to 42% for Barcelona and 46% for Stockholm. The results of the PUE in both locations show the most significant decrease due to the use of thermal containment but also thermal variable flow and the use of high efficiency thermal elements. However, a slight increase of the metric value due to IT consolidation and turn off idle server is reached. Regarding the cooling of the seasonal performance factor the most noticeable increase is shown with the application of thermal containment, thermal variable flow and the use of high efficiency thermal elements. However, the efficiency measures IT consolidation and turn off idle server lead to a slight decrease of the metric in both locations equally. The decrease of the RER with all efficiency measures applied is marginal with 2% in both locations. The IT installed capacity credit shows a dependency on IT consolidation and turn off idle server. These measures lead to a significant increase of the metric values. This behaviour is equal for the two locations whereas for Stockholm the use of green algorithm leads to decreasing values. The results of the total facility installed capacity credit show very similar tendencies except for a further dependency on the increase of supply air temperature.

When analysing the sizes of the main elements, the effect of the efficiency measures on the total air mass flow rate, the power consumption of the fans, the nominal power of the transformer and the nominal current of the switchgear is very similar to the results for concept 1 (see Subsection 7.3.2.1). Additionally, the specific value for concept 3 (cooling tower) shows a decreasing dependency on the measure using high efficiency thermal elements.

7.3.4.2 Influence of EE measures

Table 7.10 Accumulation test results for the size of the main elements in concept 3

Components	Unit	Case													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
VCCh chiller (nominal power)	kW	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Cooling tower (nominal power)	kW	1875	1875	1875	1875	1875	1875	1875	1875	1875	1875	1773	1773	1773	1773
Total air mass flow rate	t/h	768	768	768	768	768	302	302	302	302	302	302	302	302	302
Power consumption of fans	kW	94	94	94	94	94	37	37	37	37	37	37	37	37	37
Transformer (TR) (Nominal power)	kW	2185	2185	2185	2185	2185	2034	2034	2034	2034	2034	1899	1899	1899	1899
Switchgear (SWG) (Nominal current of)	kW	4169	4169	4169	4169	4169	3883	3883	3883	3883	3883	3623	3623	3623	3623
Generator (GE) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Uninterruptible Power Supply unit (UPS) (Nominal power)	kW	629	629	629	629	629	629	629	629	629	629	629	629	629	629

7.3.4.3 Influence of size

The variation of the Data Centre nominal IT power shown in Figure 7.16 is evaluated for the TCO and the RER in two locations Barcelona and Stockholm. Regarding the costs it can be analysed that the decrease with the application of all energy efficiency measures for Barcelona is 13–16% while the values for Stockholm are marginally increasing (1–2%). However, the cost values for Barcelona, are 23–41% higher than for Stockholm. The decrease of the non-renewable primary energy values with the application of the efficiency measures reaches up to 40–42%. The dependency of the nominal IT power is comparable for both locations and lead to decreasing costs of maximal 20% for Barcelona and 27% for Stockholm while the influence on the non-renewable primary energy is insignificant. The most significant decrease of the costs can be analysed from 100 kW to 500 kW compared to the next variation steps (500 kW, 1000 kW, 2000 kW, etc.). Regarding the RER, the application of energy efficiency measures lead to a slight increase of about 5% for Barcelona and 4% for Stockholm, while the size of the Data Centre does not show a major dependency on this metric.

7.3.4.4 On-site PV systems implementation

Figure 7.17 shows the results of applying on-site PV power systems to concept 3 for the different scenarios. Results are in coherence with the findings of adding PV to concept 1. PE_{nren} decreases and RER increases when the size of the PV system increases, being cost-effective in Barcelona and not economically feasible for Stockholm in terms of TCO.

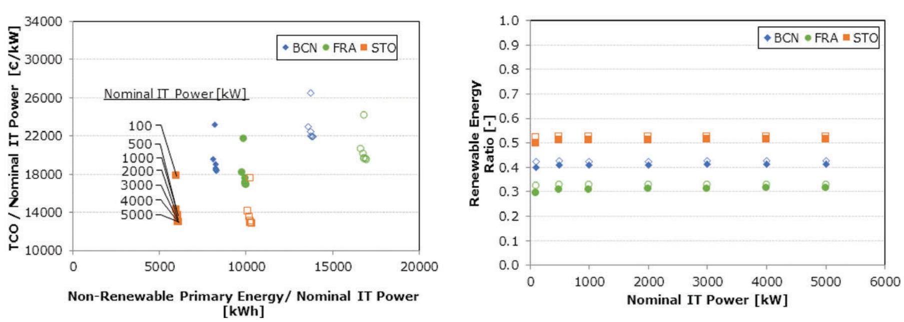


Figure 7.16 Variation of the Data Centre nominal IT power for the two locations (Barcelona and Stockholm) for concept 3. Unfilled shapes represent the reference case and filled shapes the case with all energy efficiency measures applied.

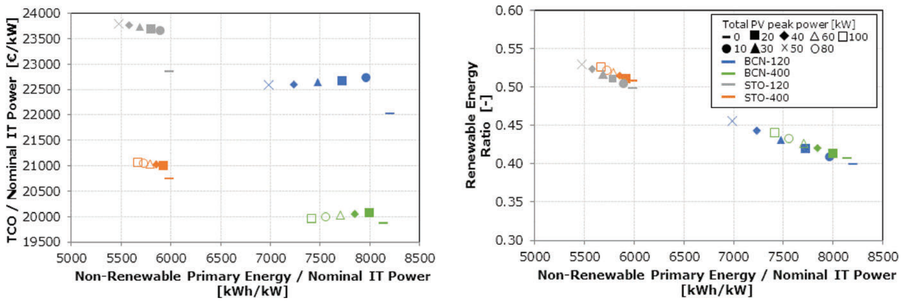


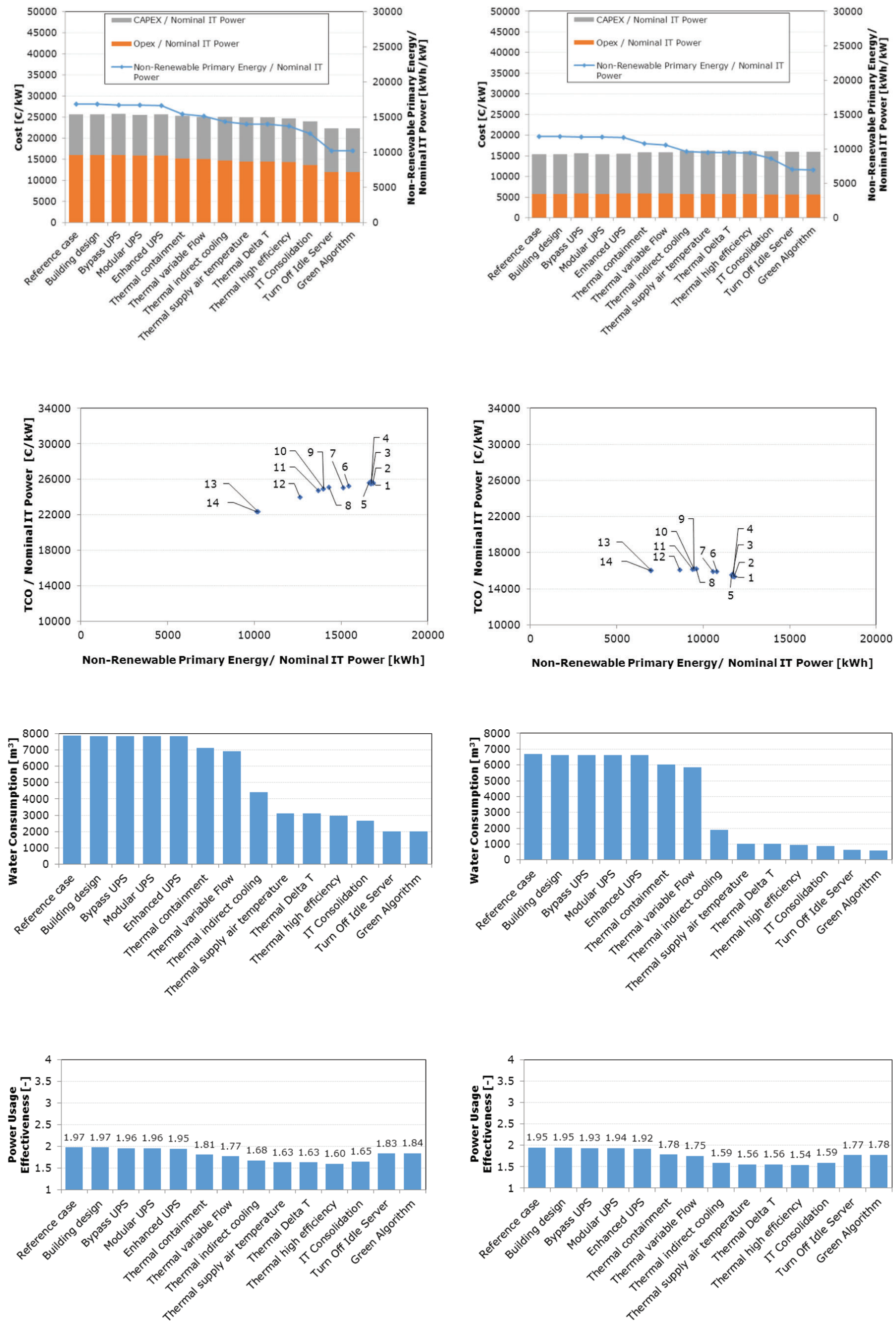
Figure 7.17 Normalized TCO (left) and RER (right) vs. normalized PE_{nren} for different scenarios when adding on-site PV power systems to concept 3.

7.3.5 Concept 4. Grid-Fed Vapour-Compression Chiller with Electrical Energy and ChilledWater Storages

7.3.5.1 Influence of EE measures

The results for each metric analysed (Figure 7.18) and the sizes of the main elements (Table 7.11) present the results of the accumulative tests for concept 4.

A significant decrease (40% for Barcelona and 41% for Stockholm) of the non-renewable primary energy values is influenced mainly by thermal containment, thermal indirect cooling, IT consolidation and turn off idle server in both locations. Due to a decreasing OPEX (25% for Barcelona) and slightly increasing CAPEX (8% for Barcelona) with the application of the measures the TCO shows a slight decrease of about 13% for Barcelona as well. For the location Stockholm the increase of the CAPEX (8%) and the decrease of the OPEX (4%) lead to a slight increase of the TCO values of about 4%. The water consumption decreases due to the application of thermal containment, thermal indirect cooling, the increase of supply air temperature, IT consolidation and turn off idle server. In both locations the highest dependency is seen for thermal indirect cooling. The overall reduction of the water consumption applying all energy efficiency measures reaches up to 75% for Barcelona and 90% for Stockholm. The results of the PUE in both locations show a slight decrease due to the use of thermal containment, thermal variable flow, thermal indirect cooling, the increase of supply air temperature and high efficiency thermal elements while IT consolidation and turn off idle server lead to slightly increasing values of the PUE. The most noticeable increase (up to 67% for Barcelona and 76% for Stockholm) of the cooling seasonal performance factor with the application of the efficiency measures can be found for thermal containment, thermal variable flow, thermal



CAPEX / Nominal IT Power
Opex / Nominal IT Power
Non-Renewable Primary Energy / Nominal IT Power
Cost [€/kW]
Non-Renewable Primary Energy/ Nominal IT Power [kWh/kW]
Reference case
Building design
Bypass UPS
Modular UPS
Enhanced UPS
Thermal containment
Thermal variable Flow
Thermal indirect cooling
Thermal supply air temperature
Thermal Delta T
Thermal high efficiency
IT Consolidation
Turn Off Idle Server
Green Algorithm
TCO / Nominal IT Power [€/kW]
Non-Renewable Primary Energy/ Nominal IT Power [kWh]
Water Consumption [m³]
Power Usage Effectiveness [-]
1.97 1.97 1.96 1.96 1.95 1.81 1.77 1.68 1.63 1.63 1.60 1.65 1.83 1.84
1.95 1.95 1.93 1.94 1.92 1.78 1.75 1.59 1.56 1.56 1.54 1.59 1.77 1.78

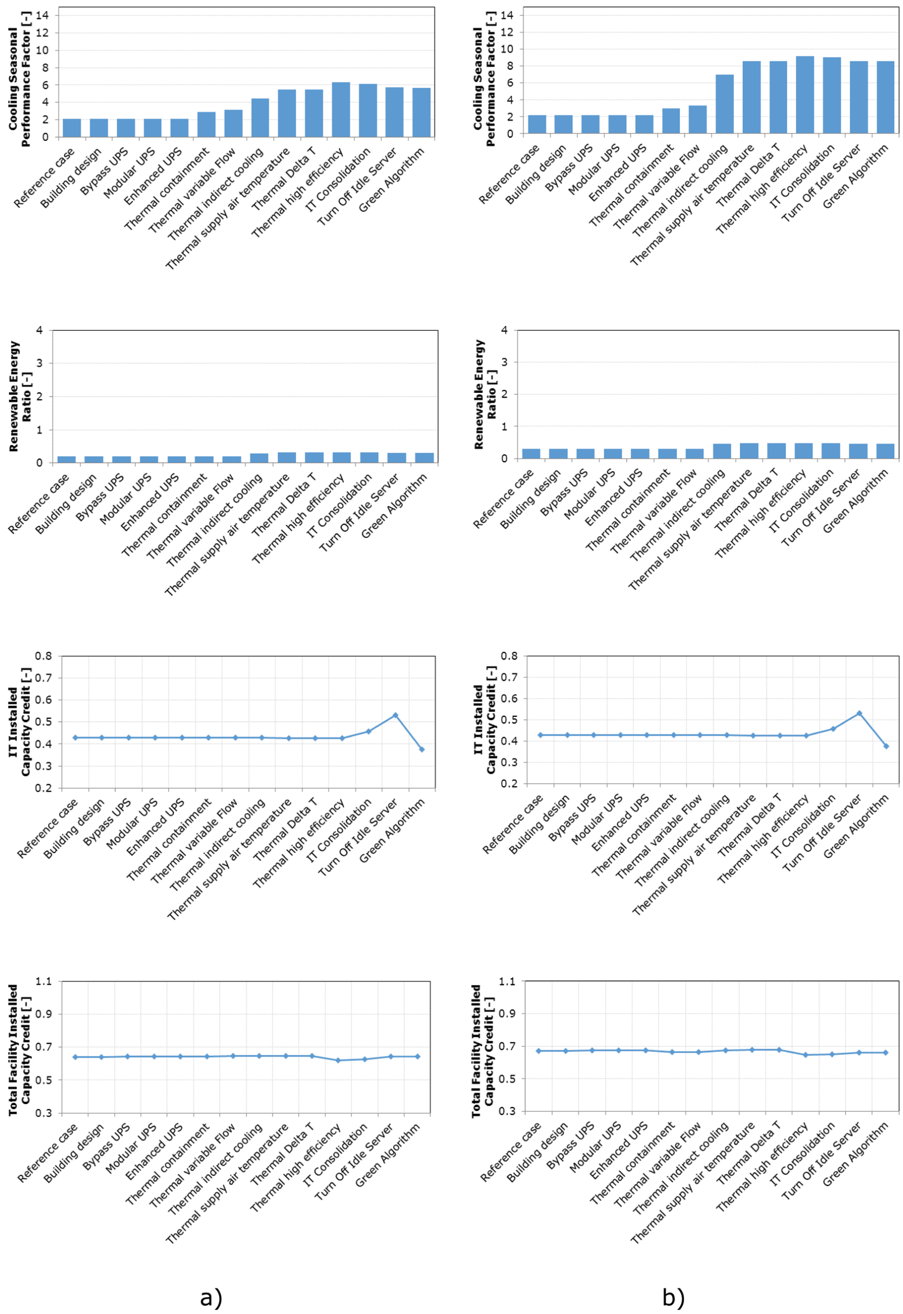


Figure 7.18 Results of accumulative tests for concept 4 in a) Barcelona and in b) Stockholm.

Table 7.11 Accumulation test results for the size of the main elements in concept 4

Components	Unit	Case													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
VCCh chiller (nominal power)	kW	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Volume of the CHWST	m^3	1237	1237	1237	1237	1237	1237	1237	1237	1237	1237	1237	1237	1237	1237
Total air mass flow rate	t/h	768	768	768	768	768	302	302	302	302	302	302	302	302	302
Power consumption of fans	kW	94	94	94	94	94	37	37	37	37	37	37	37	37	37
Transformer (TR) (Nominal power)	kW	2537	2537	2537	2537	2537	2386	2386	2386	2386	2386	2142	2142	2142	2142
Switchgear (SWG) (Nominal current of)	kW	6560	6560	6560	6560	6560	6172	6172	6172	6172	6172	5539	5539	5539	5539
Generator (GE) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Uninterruptible Power Supply unit (UPS) (Nominal power)	kW	629	629	629	629	629	629	629	629	629	629	629	629	629	629
Power Distribution unit (PDU) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500

indirect cooling, the increase of supply air temperature and the use of high efficiency thermal elements, whereas the application of IT consolidation and turn off idle servers lead to a slight decrease of the metric. This behaviour is valid for Barcelona and Stockholm as well. The RER increases significantly (61% for Barcelona and 62% for Stockholm) with all efficiency measures applied, mainly induced by the application of thermal indirect cooling and turn off idle server. The IT installed capacity credit shows an independent behaviour towards the applied measures except for IT consolidation, turn off idle server and green algorithm. The first two lead to a significant increase of the metric values (19%), while the use of green algorithm leads to decreasing values that end nearly at the reference value in both locations equally. The results of the total facility installed capacity credit show nearly no dependency on measures applied but except for a slight increase with the application of thermal containment, the use of high efficiency thermal elements and a slight increase with the applications of IT consolidation and turn off idle server. This analysis is equally valid for both locations.

When analysing the sizes of the main elements, the effect of the efficiency measures on the total air mass flow rate, the power consumption of the fans, the nominal power of the transformer and the nominal current of the switchgear show similar dependencies compared to the results for concept 1 (see Subsection 7.2.1).

7.3.5.2 Influence of size

In Figure 7.19 the variation of the Data Centre nominal IT power is shown for the TCO and the RER. Regarding the results of the TCO in the two locations Barcelona and Stockholm a notable decrease with the application of all energy efficiency measures is shown for Barcelona (9–14%) while for

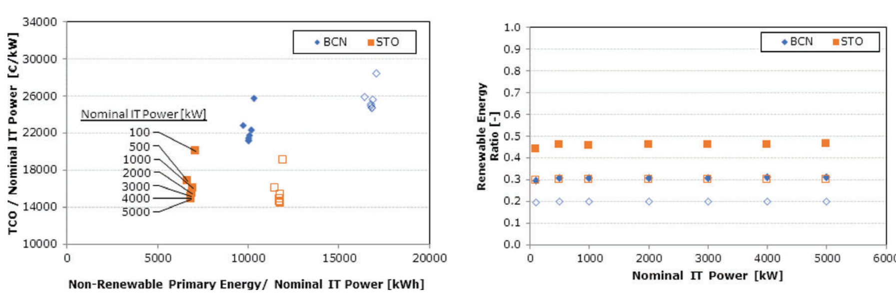


Figure 7.19 Variation of the Data Centre nominal IT power for the two locations (Barcelona and Stockholm) for concept 4. Unfilled shapes represent the reference case and filled shapes the case with all energy efficiency measures applied.

Stockholm a marginal increase can be analysed (3–5%). The absolute cost values for Barcelona are 22–42% higher than for Stockholm. The decrease of the non-renewable primary energy values with the application of the efficiency measures reaches up to 39–42% nearly equally in both locations. The dependency of the nominal IT power is comparable for both locations and lead to decreasing costs of maximal 18% for Barcelona and 26% for Stockholm while the influence on the non-renewable primary energy is nearly insignificant. The most significant decrease of the costs can be analysed from 100 kW to 500 kW compared to the next variation steps (500, 1000, 2000 etc.). When looking at the RER, the implementation of the energy efficiency strategies lead to a notable increase of about 33% for Barcelona and 35% for Stockholm, while the size of the Data Centre does not show a major dependency on this metric.

7.3.5.3 Influence of the size of TES

It is well known that the use of energy storage systems can play an important role to reduce operational costs of any infrastructure where there are differences between energy production and energy demand or between electricity prices over the day (i.e. day/night price). The main drawback of implementing TES systems in real applications is first, the investment cost which needs to be carefully analysed, and second, each TES implementation needs a careful energy analysis considering the operational boundary conditions. It is reasonable to expect that an optimal configuration, including energy storage and energy management, exists for a current situation and in particular for a specific Data Centre characteristics. For this reason, it is highly recommended to develop energy and economic dynamic models and optimize the system configuration with the real boundary conditions.

Standard Data Centres have redundant chiller which can be used to produce chilled water when the electricity cost is low during off-peak hours and store that cold in the TES system. Contrarily, when the electricity price is expensive (peak hours), the management system will enforce the tank to be discharged in order to decrease the return water temperature. The optimal configuration of the TES implementation concerns combinations of choices regarding the storage tank volume and the operational performance of the chiller used to produce cold water during off-peak hours in terms of desired chilled water temperature and return water temperature to switch on the chiller.

In order to show the methodology for TES implementation, an operative Data Centre with a total IT capacity of 140 kW is considered. This facility is currently being used to provide computing and information services for the

Polytechnic University of Catalonia, in Barcelona (Spain). The IT consumption of the infrastructure (70 racks of data and 12 racks of communication equipment) is 100 kW IT while the IT room area is of 285 m^2.

In the optimization phase the TCO, which takes also into consideration the investment cost of the TES system implemented, should be minimized. The economic objective function considers two different of expenses: the operational expenditures (OPEX) and the investment cost (CAPEX) as shown in Equation (7. 2).

$$\mathrm{TCO} = \mathrm{OPEX} + \mathrm{CAPEX} \tag{7.2}$$

where OPEX and CAPEX are calculated using Equation (7.3) and Equation (7.4), respectively.

$$\mathrm{OPEX} = \left(\sum_{i=1}^{3} \mathrm{E}^{i}_{\mathrm{chiller}} + \sum_{i=1}^{3} \mathrm{E}^{i}_{\mathrm{pump}} + \mathrm{E}_{\mathrm{CRAH}}\right) \cdot \mathrm{p} \tag{7.3}$$

where $\mathrm{E}_{\mathrm{chiller}}$ is the energy consumption of the chillers in kWh, $\mathrm{E}_{\mathrm{pump}}$ is the energy consumption of the pumps in kWh, $\mathrm{E}_{\mathrm{CRAH}}$ is the energy consumption of the CRAHs in kWh, and p is the electricity price in €/kWh.

$$\mathrm{CAPEX} = (\mathrm{tankCost} + \mathrm{waterCost}) \cdot \mathrm{V}_{\mathrm{TES}} \tag{7.4}$$

where $\mathrm{tankCost}$ is the cost for the storage tank as well as all the auxiliary equipment necessary in € and $\mathrm{waterCost}$ is the water cost.

Table 7.12 shows the decision variables of the problem as well as the theoretical upper/lower bound for the optimization process for the real Data Centre analysed. Regarding the upper/lower bound for the water storage tank volume, it makes no sense to study systems smaller than 5 m^3 since the impact will be really poor. On the other hand, the actual chiller capacity (77.7 kW_{th}) limits the storage at 150 m^3. Above this storage volume, the chiller is not able to charge the tank completely.

Table 7.12 Description of the decision variables

Decision Variable	Units	Range
Water storage tank volume	[m^3]	[5,150]
Chiller outlet water temperature set-point	[°C]	[6,12.5]
Chiller temperature difference (inlet-outlet)	[°C]	[1,5]

Table 7.13 Optimization results for both scenarios

	$T_{sp,3}$	V_{TES}	dT	Investment	Operational Expenses
Scenario	[ºC]	[m^3]	[ºC]	[€]	[€]
Scenario 1 (RenewIT)	6	64.4	2.9	55,584	141,834
Scenario 2 (Fragaki)	6	47.8	1	42,851	142,491

Table 7.13 shows the yearly operational expenses for the upper/lower bound scenarios in comparison to the reference case, in case when no TES system is incorporated into the Data Centre and with the two optimized scenarios. RenewIT and Fragaki [7] scenarios represent similar investment cost of the TES system with different lifetime period. The results show that the OPEX values for upper/lower scenarios are lower than the reference system, so the strategy of storing cold during off-peak hours is proven but the investment cost should be taken into account. For instance, the mixed bound 1 scenario provides more annual savings than Fragaki but the investment cost is much higher; therefore, it is not recommended. Table 7.13 shows the results of the optimization, presenting the optimized operational values ($T_{sp,3}$ and dT), the storage tank volume (V_{TES}) and the associated investment and operational expenses. As expected, the investment function influences drastically the final results. On one hand, in scenario 1 (RenewIT) where the investment expenses are cheaper while the lifetime is higher (25 years), the optimal configuration is for a storage tank of 64.4 m^3. On the other hand, in scenario 2 (Fragaki), where the lifetime of the system is being reduced to 15 years, the optimal volume tank is smaller (47.8 m^3). The storage volume then affects the working temperatures of the chiller. In both cases, the desired chilled water temperature from the chiller ($T_{sp,3}$) is the lower bound (6ºC). This phenomenon clearly opens the door to explore other systems which allow producing water at lower temperatures by the use of some refrigerant. Another strategy will be to use ice storage tanks. However, depending on the scenario analysed, the activation temperature is different. While for scenario 1, dT is 2.9°C and therefore $T_{ACT,3}$ is 8.9ºC, for scenario 2 dT is the lower bound, with $T_{ACT,3}$ of 7ºC.

Table 7.14 summarizes all the economic figures already described for both scenarios. These economic figures demonstrate the feasibility of the implementation of TES into Data Centre portfolio. However, the economic benefit after the lifetime of the system is not encouraging while in the future the cost of the electricity may change and therefore it is difficult to conclude that the investment for the TES system implementation, in particular with scenario 1, is beneficial for the Data Centre presented. For this reason, the impact of the uncertainty of the electricity price in the future is also studied.

Table 7.14 Economical figures for both scenarios analysed

Scenario	Investment Cost [€]	Yearly Energy Cost [€ /y]	Annual Savings [€ /y]	NPV [€]	Payback [years]	BCR [–]
Scenario 1 (RenewIT)	55,584	144,058	4,593	53,373	<12	1.52
Scenario 2 (Fragaki)	42,851	145,348	3,936	16,739	<11	1.15

When thermal or electric energy storage is implemented in any facility, the electricity price difference between peak and off-peak is more important than the absolute value of the electricity. Two scenarios varying the electricity price are evaluated considering that the average electricity price is the same (0.11 €/kWh) for each scenario while the amplitude between peak and off-peak hours is modified. Scenario 1 assumes an amplitude of 0.06 €/kWh and scenario 2 0.12 €/kWh. In this context, the implementation of a TES system is studied considering a storage tank of 50 m^3 and the operational conditions as $T_{sp,3}$ = 6ºC and dT = 2ºC. Figure 7.20 and Figure 7.21 show the yearly operational expenses for different systems: a Data Centre with no TES system (no TES), a Data Centre with TES and the actual electricity price (reference) and the same Data Centre with different electricity prices (scenario 1 and scenario 2). The results clearly show the importance of the

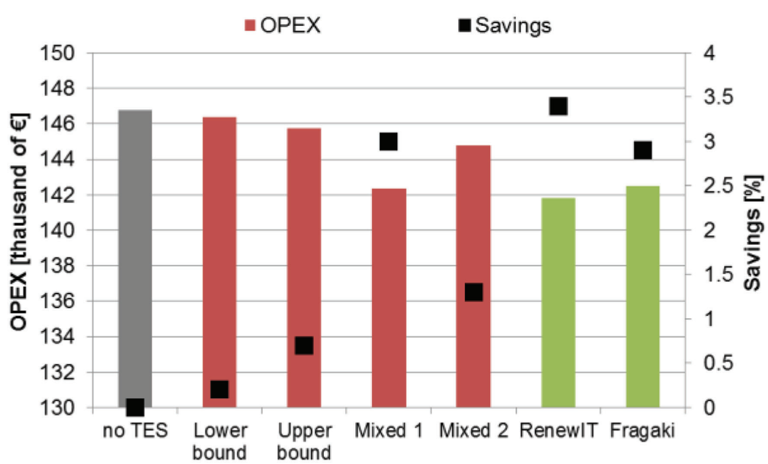


Figure 7.20 Yearly operational expenses for different scenarios.

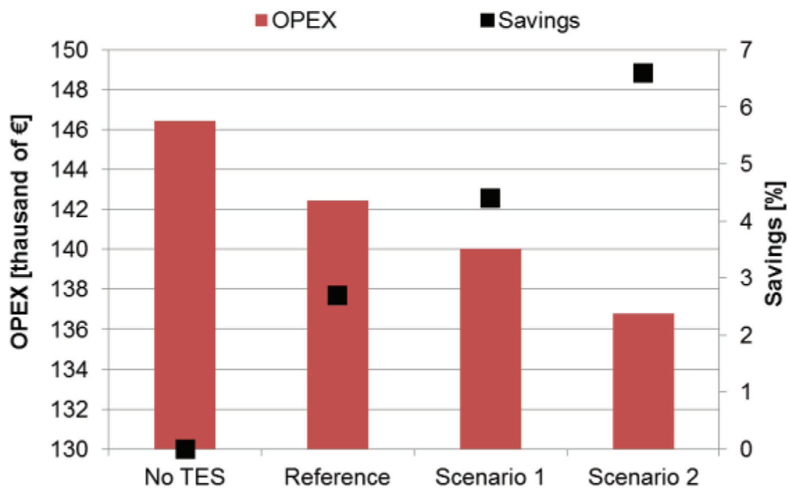


Figure 7.21 Yearly operational expenses for different electricity scenarios.

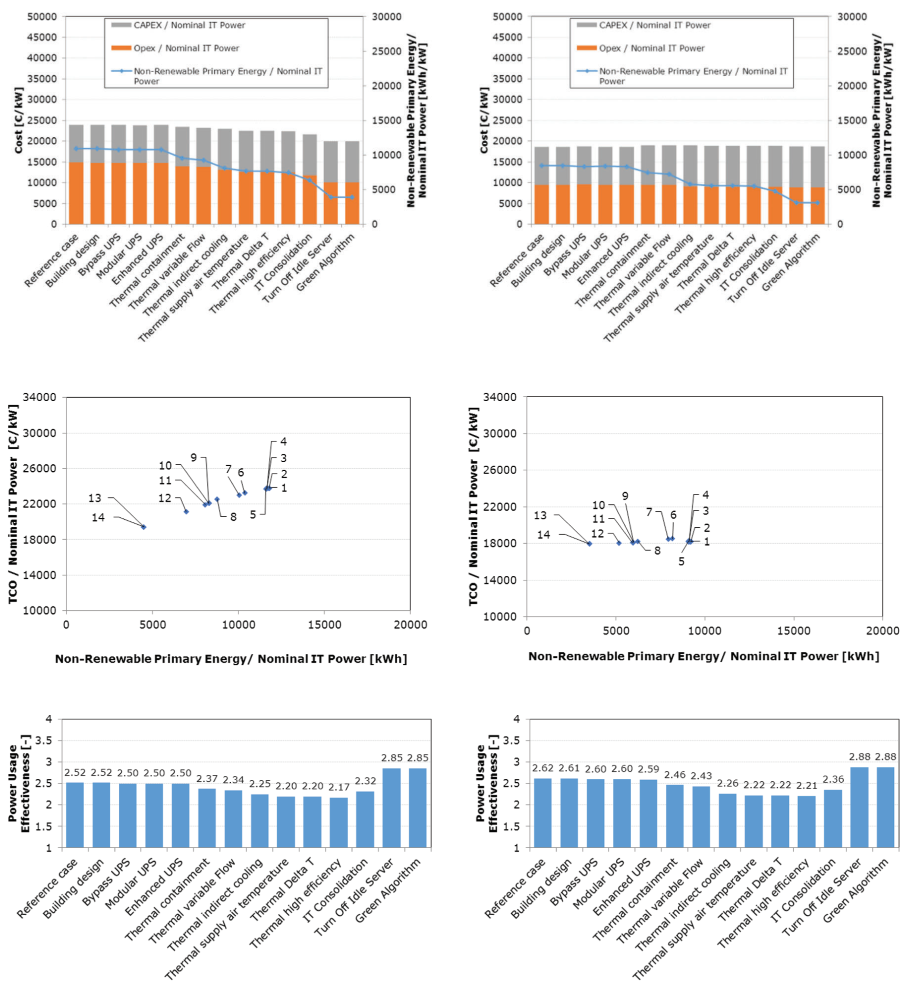
difference between peak and off-peak electricity price. For scenario 2, where this difference is higher, the operational savings can increase up to 7%. This results demonstrate that the use of TES is preferable in such countries where the electricity variation between day and night is important like in the USA where the difference can be higher than 0.08 €/kWh.

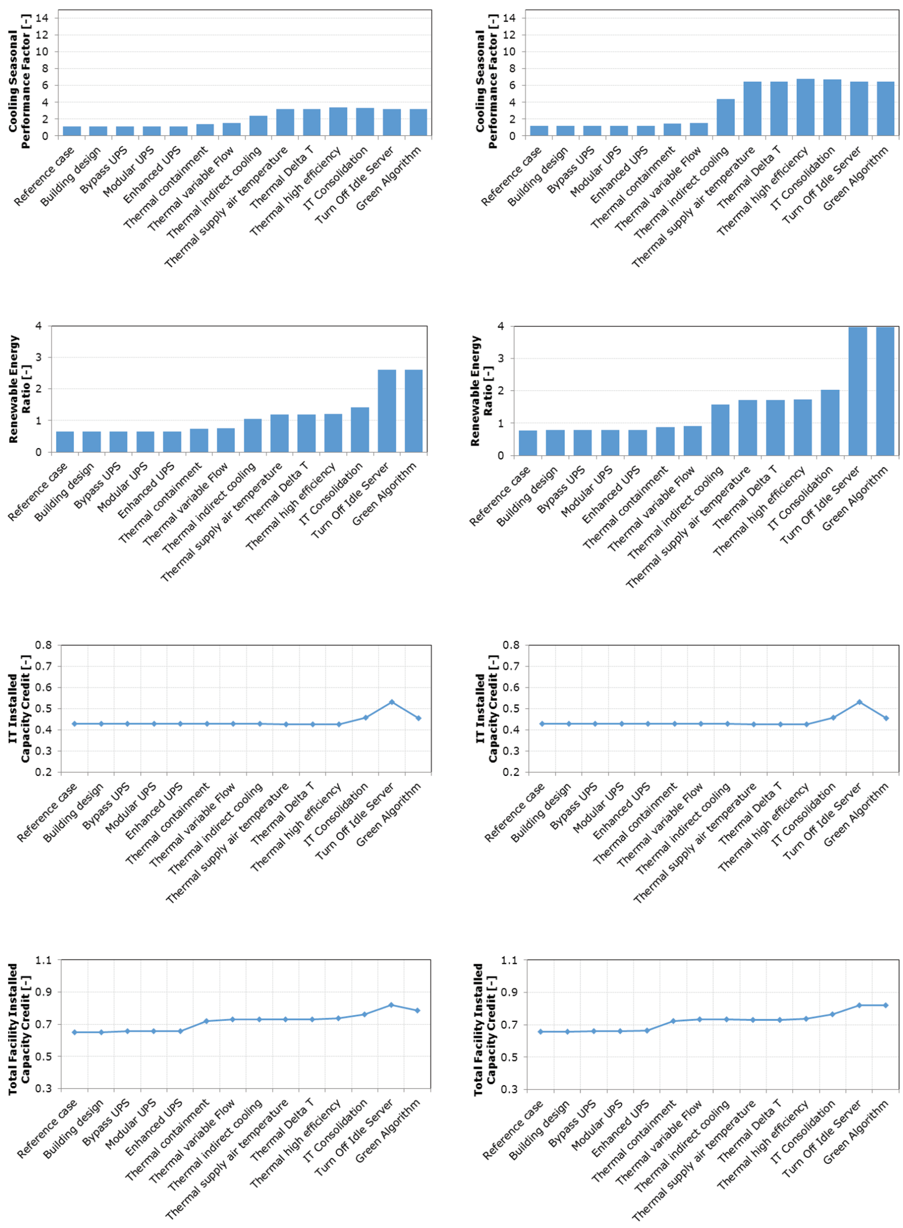
7.3.6 Concept 5. Biogas Fuel Cell with Absorption Chiller

7.3.6.1 Influence of EE measures

The results for each metric analysed (Figure 7.22) and the sizes of the main elements (Table 7.15) present the results of the accumulative tests for concept 5.

The non-renewable primary energy is influenced mainly by thermal containment, thermal indirect cooling, IT consolidation and turn off idle server in both locations analysed. These measures lead to a significant decrease (64% for Barcelona and 63% for Stockholm) of the metric values. Due to a decreasing OPEX (32% for Barcelona) and slightly increasing CAPEX (8% for Barcelona) with the application of the measures the TCO shows a slight decrease of about 17% for Barcelona as well. For Stockholm the increase of the CAPEX (8%) and the decrease of the OPEX (6%) lead to a marginal increase of the TCO values of about 1%. The results of the PUE in both locations decrease (12% for Barcelona and 14% for Stockholm) due to the use of thermal containment, thermal variable flow, thermal indirect cooling, the increase of supply air temperature and high efficiency thermal elements while the application of IT consolidation and turn off idle server lead to notable increasing values (26% for Barcelona and Stockholm) of the PUE. The significant increase (up to 66% for Barcelona and 82% for Stockholm) of the cooling seasonal performance factor with the application of the efficiency measures is mainly caused by thermal indirect cooling, the increase of supply air temperature but also thermal containment, thermal variable flow, and the use of high efficiency thermal elements contribute to this increase, whereas the application of IT consolidation and turn off idle servers lead to a slight decrease





a) b)

Figure 7.22 Results of accumulative tests for concept 5 in a) Barcelona and in b) Stockholm.

Table 7.15 Accumulation test results for the size of the main elements in concept 5

Components	Unit	Case													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Absorption chiller (nominal power)	kW	288	288	288	288	288	288	288	288	288	288	288	288	288	288
Cooling tower (nominal power)	kW	634	634	634	634	634	634	634	634	634	634	634	634	634	634
Total air mass flow rate	t/h	768	768	768	768	768	302	302	302	302	302	302	302	302	302
Power consumption of fans	kW	94	94	94	94	94	37	37	37	37	37	37	37	37	37
Transformer (TR) (Nominal power)	kW	1873	1873	1873	1873	1873	1722	1722	1722	1722	1722	1647	1647	1647	1647
Switchgear (SWG) (Nominal current of)	kW	3574	3574	3574	3574	3574	3287	3287	3287	3287	3287	3144	3144	3144	3144
Generator (GE) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Uninterruptible Power Supply unit (UPS) (Nominal power)	kW	629	629	629	629	629	629	629	629	629	629	629	629	629	629
Power Distribution unit (PDU) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500

of the metric. This behaviour is valid for Barcelona and Stockholm as well. Regarding the RER an increase of 61% for Barcelona and 35% for Stockholm can be analysed with all efficiency measures applied, mainly induced by the application of thermal indirect cooling. The IT installed capacity credit shows an independent behaviour towards the applied measures except for IT consolidation, turn off idle server and green algorithm. The first two lead to a significant increase of the metric values, while the use of green algorithm leads to decreasing values that end up 11% below the reference value in both locations equally. The results of the total facility installed capacity credit show nearly no dependency on measures applied but except for a slight increase (about 20% for Barcelona and Stockholm) with the application of thermal containment, high efficiency thermal elements, IT consolidation and turn off idle server. For Barcelona a slight decrease can be found for the application of green algorithm. Other than that the analysis is equally valid for both locations.

When analysing the sizes of the main elements, the effect of the efficiency measures on the total air mass flow rate, the power consumption of the fans, the nominal power of the transformer and the nominal current of the switchgear show similar dependencies compared to the results for concept 1 (see Subsection 7.3.2.1).

7.3.6.2 Influence of size

Figure 7.23 shows the variation of the Data Centre nominal IT power for concept 5. The evaluation is done for the TCO and the RER in the two locations Barcelona and Stockholm. Regarding the costs it can be analysed that a notable decrease with the application of all energy efficiency measures is shown for Barcelona (12–18%) while for Stockholm a marginal increase can

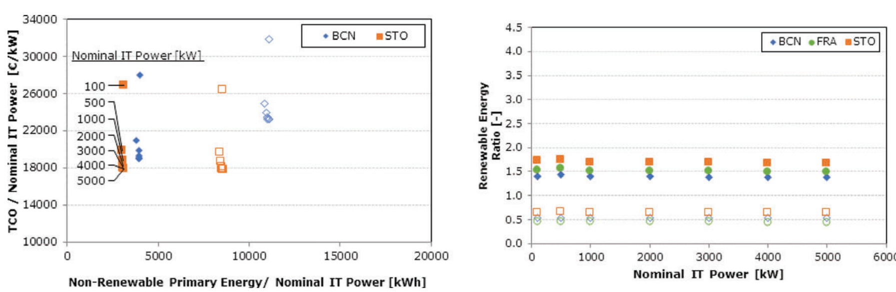


Figure 7.23 Variation of the Data Centre nominal IT power for the two locations (Barcelona and Stockholm) for concept 5. Unfilled shapes represent the reference case and filled shapes the case with all energy efficiency measures applied.

be analysed (0.2–1.6%). However, the absolute cost values for Barcelona are 4–23% higher. The decrease of the non-renewable primary energy values with the application of the efficiency measures reaches up to 64% equally in both locations. The dependency of the nominal IT power is comparable for both locations and lead to decreasing costs of maximal 32% for Barcelona and 34% for Stockholm while the influence on the non-renewable primary energy is nearly insignificant. The most significant decrease of the costs can be analysed from 100 kW to 500 kW (up to 21% for Barcelona and 26% for Stockholm) compared to the next variation steps (500 kW, 1000 kW, 2000 kW, etc.). Regarding the RER the application of energy efficiency measures lead to a notable increase of maximal 62% for Barcelona and Stockholm equally. However the size of the Data Centre does not show a notable dependency on this metric.

7.3.6.3 Influence of absorption chiller sizes and potential heat reuse

Figure 7.24 presents the results of a parametric analysis for concept 5 (Data Centre based on biogas fuel-cell driving an absorption chiller) for different scenarios. Figure 7.18 (right) only shows results for 400 kW_{IT} Data Centre to improve the readability. The variation of two parameters has been analysed. One is the amount of heat produced by the facility which can be reused for other purposes outside the Data Centre: this is characterized by a ratio between 0.2 and 1.0, meaning 1.0 that 100% of the heat can be reused outside the Data Centre. The other parameter is the size of the absorption chiller which is characterized by a parameter from 0.2 to 0.5 which is the ratio between

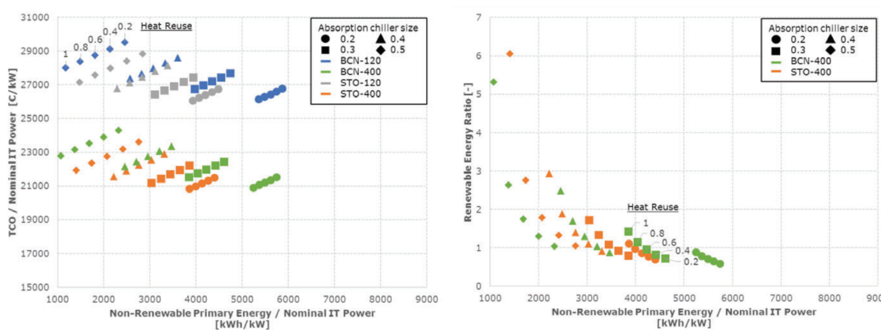


Figure 7.24 Normalized TCO (left) and RER (right) vs. normalized PE_{nren} for different scenarios, relative absorption chiller sizes and amount of heat reuse ratio for concept 5.

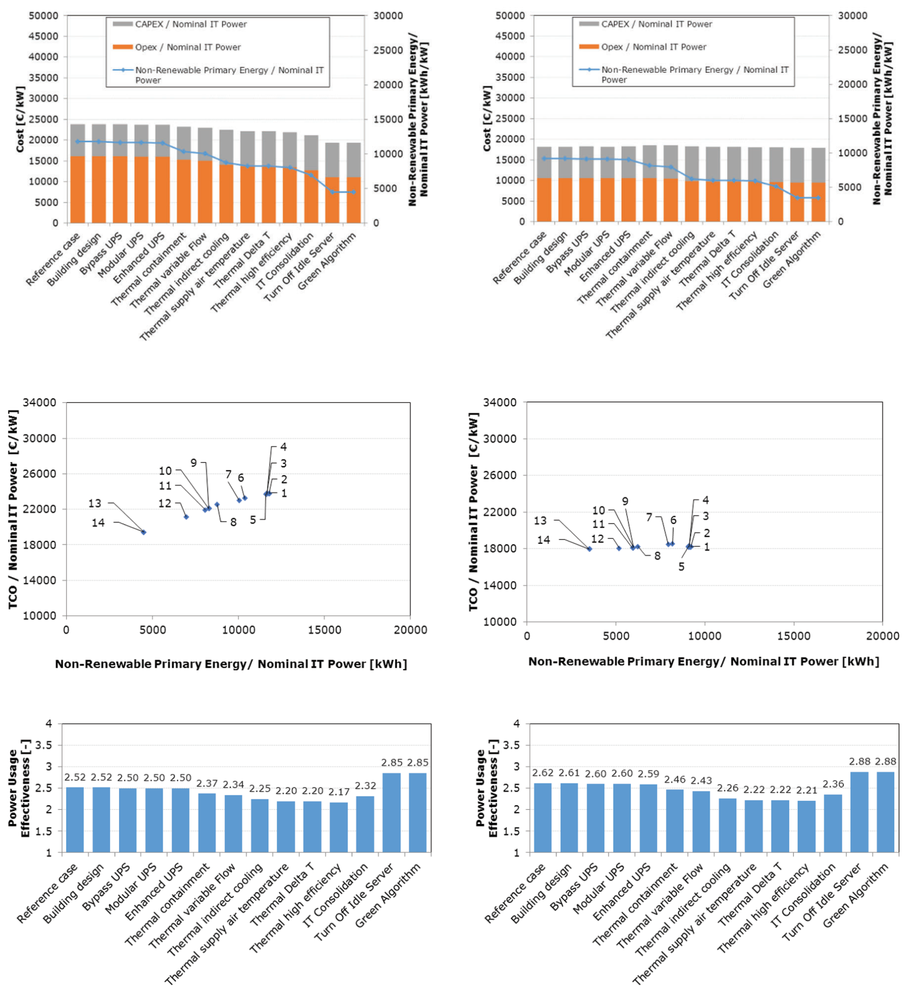
absorption cooling capacity and the total cooling power of the Data Centre. The results in Figure 7.18 show that an increase of the absorption chiller size is not a cost-effective measure although it has an important effect on the reduction of the PE_{nren} and the increase of RER. For a ratio of the absorption chiller greater than 0.3, RER values are close to or great than 1.0 which indicates that the Data Centre facility is becoming a positive producer of primary energy even with low ratios of heat reuse. When the potential heat reuse is being reduced, the TCO increases as well as the PE_{nren} as consequence of the reduction of the exported heat.

7.3.7 Concept 6. Reciprocating Engine CHP with Absorption Chiller

7.3.7.1 Influence of EE measures

The results for each metric analysed (Figure 7.25) and the sizes of the main elements (Table 7.16) present the results of the accumulative tests for concept 6.

The results of the non-renewable primary energy are influenced mainly by thermal containment, thermal indirect cooling, IT consolidation and turn off idle server in both locations. These measures lead to a significant decrease (62% for Barcelona and Stockholm) of the metric values. Due to a decreasing OPEX (32% for Barcelona) and slightly increasing CAPEX (9% for Barcelona) with the application of the measures the TCO shows a slight decrease of about 18% for Barcelona as well. For the location Stockholm the increase of the CAPEX (9%) and the decrease of the OPEX (10%) lead to a slight decrease of the TCO values of about 1%. Regarding the results of the PUE in both locations a slight decrease of 13% for Barcelona and 15% for Stockholm can be analysed due to the use of thermal containment, thermal variable flow, thermal indirect cooling, the increase of supply air temperature and high efficiency thermal elements while IT consolidation and turn off idle server lead to increasing PUE values (23% for Barcelona and Stockholm) that reach even higher values than the reference case (11% for Barcelona and 9% for Stockholm). The significant increase (up to 66% for Barcelona and 82% for Stockholm) of the cooling seasonal performance factor with the application of all efficiency measures is caused mainly by thermal indirect cooling and the increase of supply air temperature but also thermal containment, thermal variable flow, and the use of high efficiency thermal elements contribute to this increase, whereas the application of IT consolidation and turn off idle servers lead to a marginal decrease of the metric. This behaviour is valid for Barcelona and Stockholm as well. For the RER an exceptional high increase of 75% for Barcelona and 80% for Stockholm with all efficiency measures applied can be analysed. This is mainly induced by the application of thermal indirect cooling, the increase of supply air temperature, IT consolidation and turn off idle server. Concerning the IT installed capacity credit the applied measures show an independent behaviour towards the applied measures except for IT consolidation, turn off idle server and green algorithm. While the first two lead to a significant increase of the metric values, the use of green algorithm



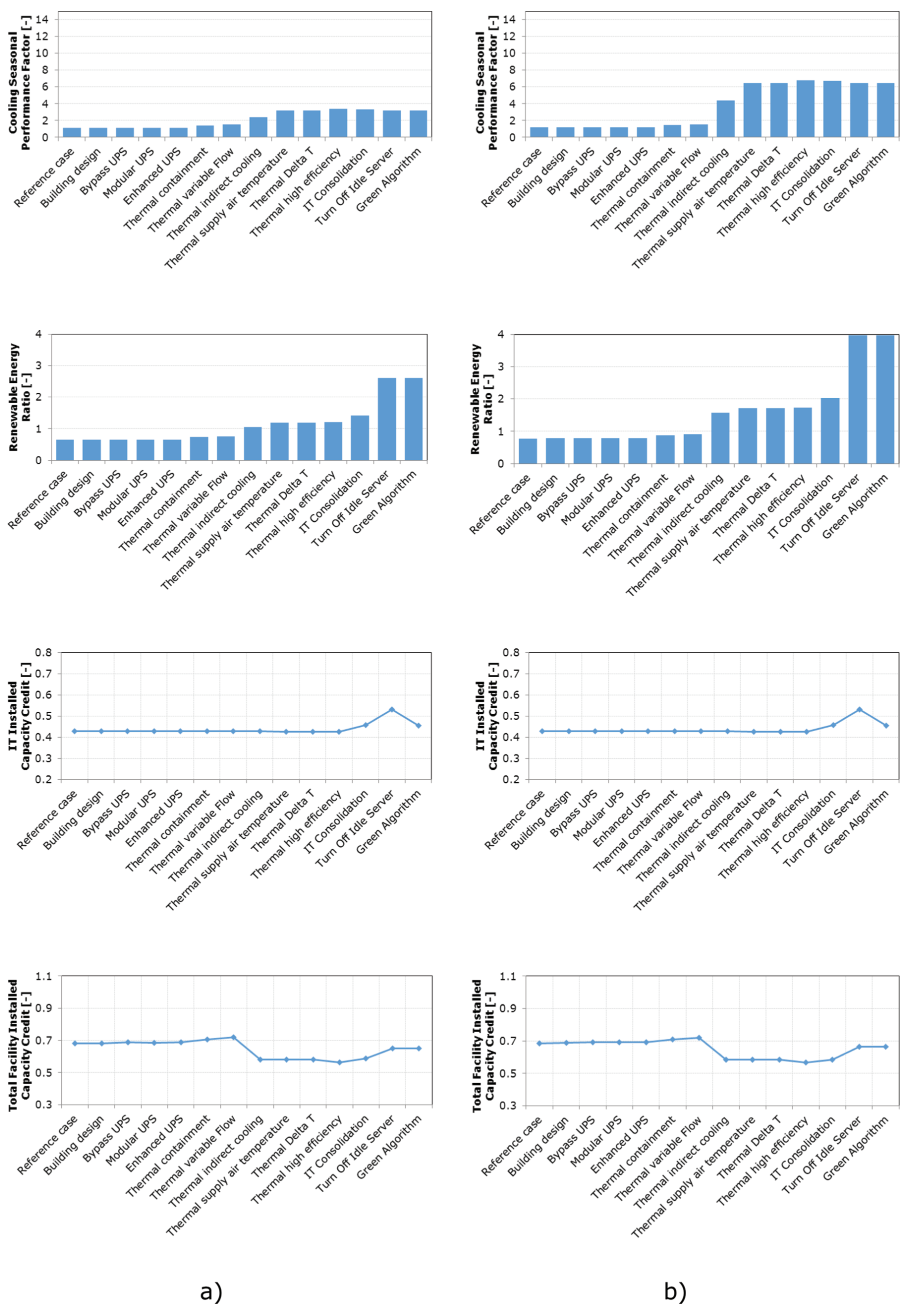


Figure 7.25 Results of accumulative tests for concept 6 in a) Barcelona and in b) Stockholm.

Table 7.16 Accumulation test results for the size of the main elements in concept 6

		Case													
Components	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Absorption chiller (nominal power)	kW	288	288	288	288	288	288	288	288	288	288	288	288	288	288
Cooling tower (nominal power)	kW	490	490	490	490	490	490	490	490	490	490	490	490	490	490
Total air mass flow rate	t/h	768	768	768	768	768	302	302	302	302	302	302	302	302	302
Power consumption of fans	kW	94	94	94	94	94	37	37	37	37	37	37	37	37	37
Transformer (TR) (Nominal power)	kW	1870	1870	1870	1870	1870	1720	1720	1720	1720	1720	1645	1645	1645	1645
Switchgear (SWG) (Nominal current of)	kW	3569	3569	3569	3569	3569	3283	3283	3283	3283	3283	3139	3139	3139	3139
Generator (GE) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Uninterruptible Power Supply unit (UPS) (Nominal power)	kW	629	629	629	629	629	629	629	629	629	629	629	629	629	629
Power Distribution unit (PDU) (Nominal power)	kW	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500

leads to decreasing values that reach nearly the reference values in both locations equally. The results of the total facility installed capacity credit show a dependency on several measures applied equally in both locations. A slight increase can be shown with the application of thermal containment, thermal variable flow, IT consolidation and turn off idle server whereas the use of thermal indirect cooling and high efficiency thermal elements leads to a decrease of the values.

When analysing the sizes of the main elements, the effect of the efficiency measures on the total air mass flow rate, the power consumption of the fans, the nominal power of the transformer and the nominal current of the switchgear show similar dependencies compared to the results for concept 1 (see Subsection 7.3.2.1).

7.3.7.2 Influence of size

The variation of the Data Centre nominal IT power shown in Figure 7.26 is evaluated for the TCO and the RER in two locations Barcelona and Stockholm. Regarding the costs it can be analysed that the decrease with the application of all energy efficiency measures is more distinctly for Barcelona (12–1%) than for Stockholm (0.2–2%). However, the absolute cost values for Barcelona are 6–25% higher. The decrease of the non-renewable primary energy values with the application of the efficiency measures reaches up to 62% equally in both locations. The dependency on the nominal IT power is comparable for both locations and lead to decreasing costs of maximal 24% for Barcelona and 25% for Stockholm while the influence on the non-renewable primary energy is negligible. The most significant decrease of the costs can be analysed from 100 kW to 500 kW (up to 14% for Barcelona and 18% for Stockholm)

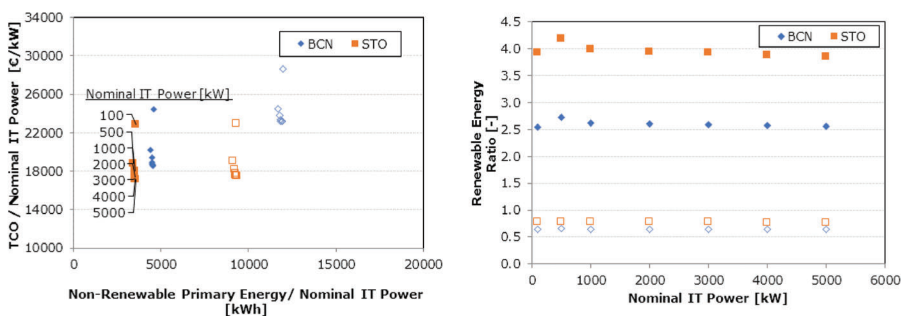


Figure 7.26 Variation of the Data Centre nominal IT power for the two locations Barcelona and Stockholm for concept 6. Unfilled shapes represent the reference case and filled shapes the case with all energy efficiency measures applied.

compared to the next variation steps (500 kW, 1000 kW, 2000 kW, etc.). Regarding the RER the application of energy efficiency measures lead to a notable increase of maximal 75% for Barcelona and 80% for Stockholm, while the size of the Data Centre just shows a minor dependency on this metric.

7.3.7.3 Influence of absorption chiller sizes and potential heat reuse

Figure 7.27 presents the results of a parametric analysis for concept 6 (Data Centre based on CHP – biogas engine driving an absorption chiller) for all the concepts. As in concept 5, the variation of two parameters has been analysed. One is the amount of heat produced by the facility which can be reused for other purposes outside the Data Centre; the other parameter is the size of the absorption chiller. The results in Figure 7.19 show the same tendency than the ones for concept 4. An increase of the absorption chiller size is not a cost-effective measure although it has an important effect on the reduction of the PE_{nren} and the increase of RER. As well as the amount of heat that can be reused is reduced (lower values of heat reuse ratio) the facility becomes more expensive to operate and PE_{nren} increases.

7.4 Other Aspects Influencing Data Centre Energy Consumption

7.4.1 Influence of the IT Load Profile

The objective of this section is to show that TCO and energy consumption are influenced by the IT load profile (how the IT facility is used). To do so, a Data Centre of 1000 kW of IT power capacity located in Barcelona is

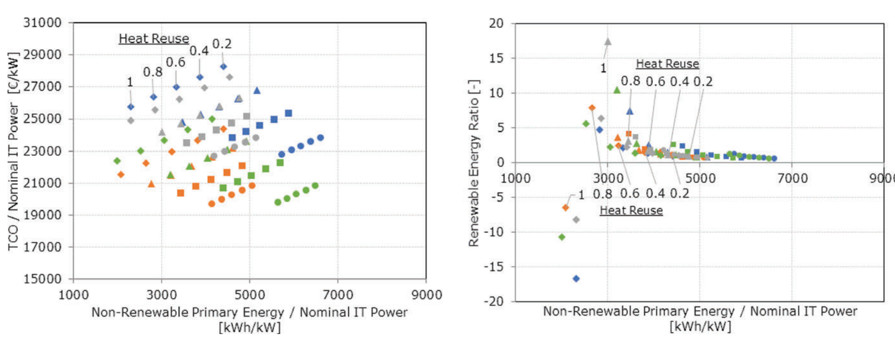


Figure 7.27 Normalized TCO (left) and RER (right) vs. normalized PE_{nren} for different scenarios, absorption chiller sizes and amount of heat reuse ratio for concept 6.

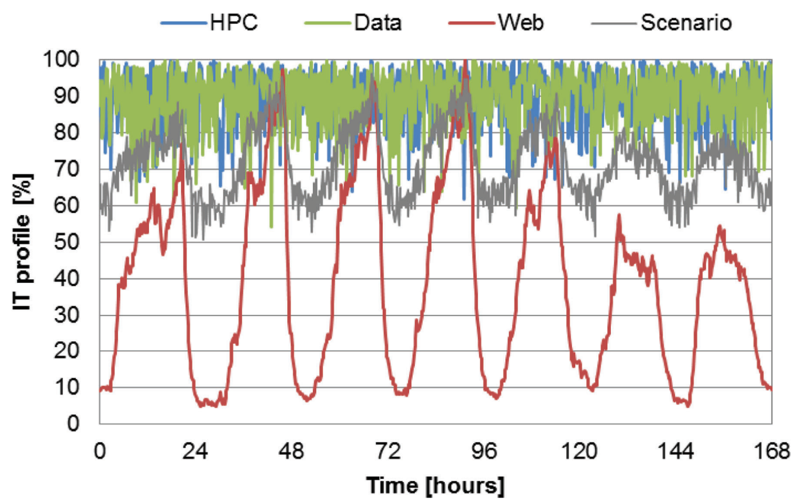


Figure 7.28 IT load profile for different scenarios.

simulated under different IT load profiles (HPC, Web, Data and mixed), as shown in Figure 7.28. Table 7.17 shows the main characteristics of the facility modelled.

Figure 7.29 shows the results (TCO and non-renewable primary energy consumption) for the four scenarios selected. Notice that in all the scenarios the CAPEX is exactly the same, so solely the IT load profile is varied. The highest energy consumption and therefore the highest TCO are experienced where HPC profile is computed, followed by the mixed scenario. This phenomenon

Table 7.17 Main parameters for the Data Centre investigated

Parameter	Unit	BCN-1000
Location	[–]	Barcelona
IT power capacity	[kW]	1000
Rack density	[kW/rack]	4
Occupancy ratio	[–]	1
Safety margin factor	[–]	0.8
White space area	[m^2]	750
IT Load profile	[–]	Mixed/Data/Web/HPC
Average electricity price	[€/kW·h_{el}]	0.0988
Average ratio renewables in the grid	[–]	0.36
$w_{del,total,el}$ (average)	[–]	2.29
$w_{del,nren,el}$ (average)	[kW·h_{PE}/kW·h_{el}]	1.83

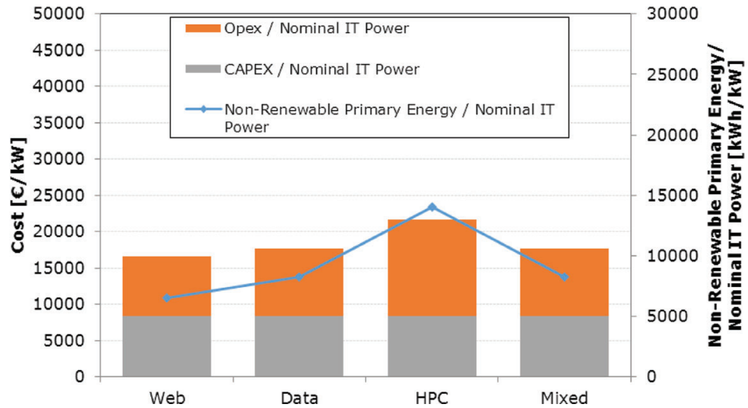


Figure 7.29 Simulation results comparing different IT load profiles.

is mainly due to the following facts: i) the IT load profile (demand) is higher for HPC ii) the power consumption associated to HPC is higher.

Figure 7.30 shows the normalized energy consumption of the IT equipment for an entire year and the normalized IT load demand. Assuming that the maximum IT load demand is where the IT load is 100% all year long, both HPC and Data load have a normalized IT load of 90% while for the purely Web load it is 40%. Notice that for the same IT load demand, a Data Centre running HPC loads consumes more energy than a Data Centre running Data load.

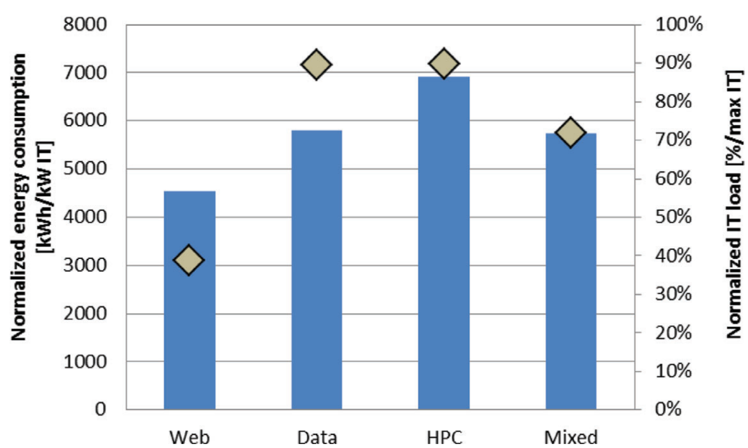


Figure 7.30 Simulation results comparing different IT load profiles.

7.4.1.1 Influence of the rack density, occupancy, and oversizing factors

This section aims to show the influence of the rack density, the occupancy ratio and the safety margin factor in the Data Centre behaviour. The TCO and the non-renewable primary energy are the metrics used to show the results and comparison between scenarios. Table 7.18 shows the main characteristics of the Data Centre analysed for a traditional energy/power supply (concept 1) without on-site renewable power systems. The safety margin factor is used to limit the maximum IT power capacity that the servers can run in the installation. As an example, a safety margin factor of 0.8 means that the maximum IT power consumption would be 80% of the total IT power capacity (1000 kW). The occupancy ratio means the ratio of installed IT, lack of occupancy is a lack of IT equipment. Therefore, for a Data Centre (power capacity of 1000 kW) with a safety margin factor of 0.8 and an occupancy ratio of 0.5, the maximum IT power consumption from the servers is 400 kW. The white space area basically depends on the nominal IT power capacity and the rack density (kW per rack). It was estimated using average ratios for floor occupied by a rack following industry used values.

Figure 7.31 shows the normalized TCO and non-renewable primary energy consumption for a constant safety margin factor of 0.8 and different values of rack density and occupancy ratio. It can be seen that when the rack density is increased the TCO is reduced due to a lower white space area needs and more compact installations. Moreover, as the occupancy ratio increases the energy consumption and therefore the TCO is increased. This phenomenon is basically because more IT load is computed in the Data Centre.

Table 7.18 Specific assumptions for the investigated Data Centre, Base case scenario for the location Barcelona varying the rack density, occupancy ratio and safety margin factor

Parameter	Unit	BCN-1000
Location	[–]	Barcelona
IT power capacity	[kW]	1000
Rack density	[kW/rack]	2 .. 10 (step 2)
Occupancy ratio	[–]	0.2 .. 1.0 (step 0.1)
Safety margin factor	[–]	0.7 .. 1.0 (step 0.1)
IT Load profile	[–]	Mixed
Average electricity price	[€/kW·h_{el}]	0.0988
Average ratio renewables in the grid	[–]	0.36
$w_{del,total,el}$ (average)	[–]	2.29
$w_{del,nren,el}$ (average)	[kW·h_{PE}/kW·h_{el}]	1.83

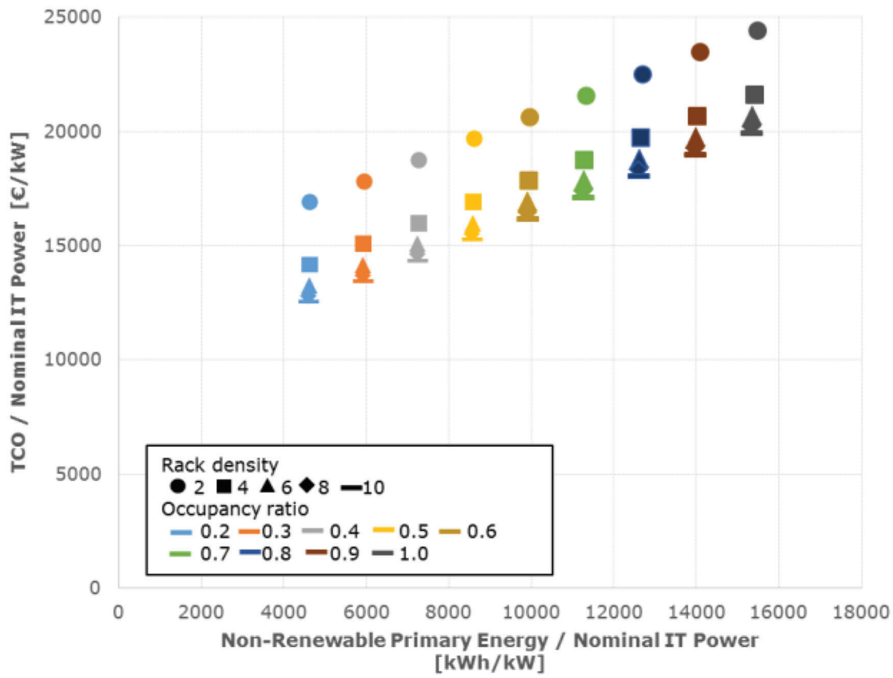


Figure 7.31 TCO and Non-renewable primary energy for different rack density and occupancy ratio using a constant safety margin factor of 0.8.

Figure 7.32 shows the normalized non-renewable primary energy in function of the safety margin factor for a constant rack density of 4 kW/rack. In this situation, the lower the safety margin factor, the lower the non-renewable primary energy consumption. This effect is due to the safety margin that limits the maximum IT power consumption, and therefore the Data Centre consumes less energy since it computes less IT load. This can also be seen in Figure 7.33, where the IT installed capacity credit is shown under the same boundary conditions. This metric shows the available IT capacity of the Data Centre, which defines the unused IT capacity and is calculated as the relation between the actual IT peak power of the system and the maximum IT peak power that the installation can handle. It is seen that for low safety margin factors, the IT installed capacity credit is higher and therefore the unused IT capacity is higher. This means that the Data Centre has a facility oversized where the PUE is higher as the safety margin factor decreases, as it is shown in Figure 7.34.

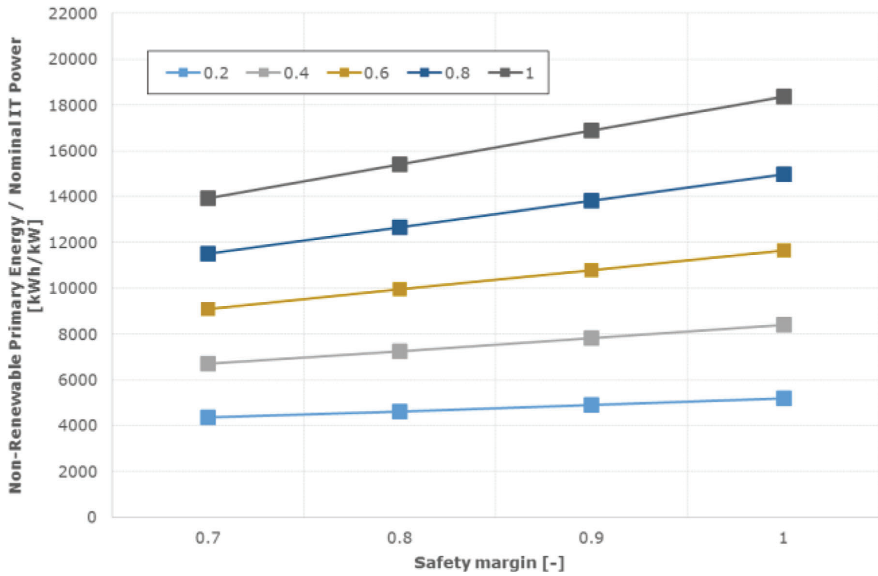


Figure 7.32 Non-renewable primary energy in function of the safety margin for a constant rack density of 4 kW/rack.

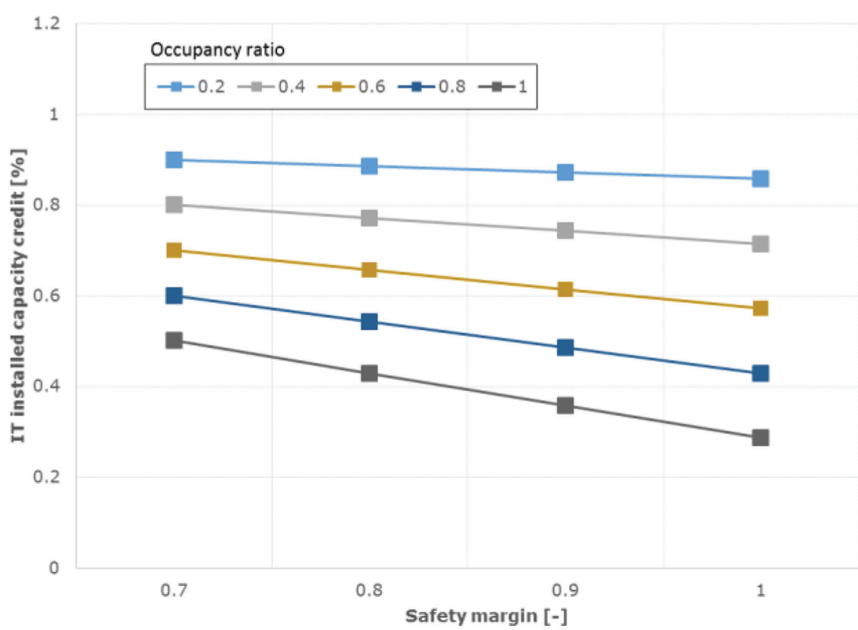


Figure 7.33 IT installed capacity credit in function of the safety margin factor and occupancy ratio for a constant rack density of 4 kW/rack.

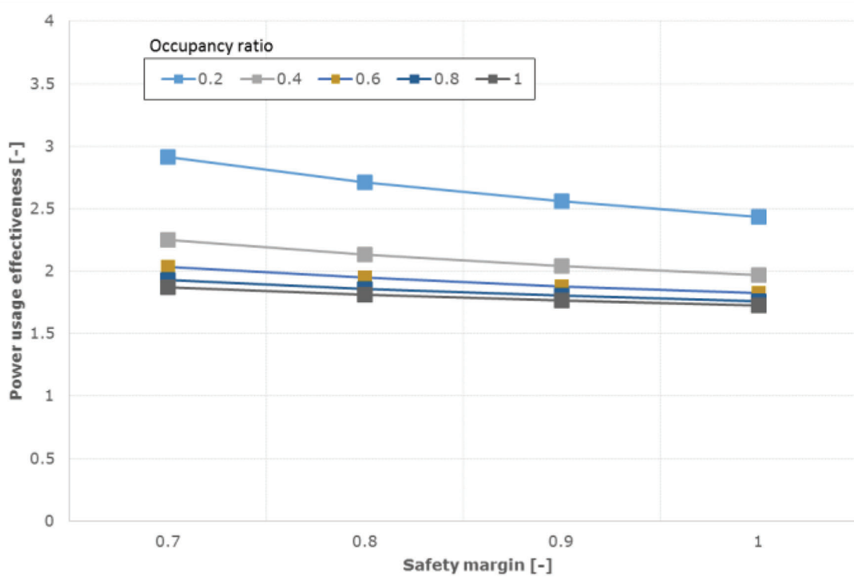


Figure 7.34 PUE in function of the safety margin factor and the occupancy ratio for a constant rack density of 4 kW/rack.

In predesign phases, instead of using the safety margin factor, the oversizing safety margin is normally used which defines the ratio between the total installed IT capacity (i.e. 1000 kW) and the maximum expected IT power consumption. The resulting extra capacity is to cover either an unexpected addition to the IT load or an unexpected impairment of the component capacity. So, the design of the power and cooling system is usually oversized in order to cover future IT load expansions. This obviously would increase the CAPEX and decrease the OPEX when working at partial loads. Figure 7.35 shows the TCO and the PUE of a facility of 1000 kW IT power capacity in function of the oversizing safety margin (from no oversized to 30% oversized) when the occupancy ratio is 80% and the average rack density is 5 kW per rack. These results clearly show how the initial investment cost (CAPEX) is higher when the oversizing safety margin is higher as well as the operational costs (OPEX) due to a reduction of the efficiency of the systems (i.e. UPS). As expected, the PUE also increases when the facility is not fitted with the IT load. These phenomenons clearly show why it is crucial to build modular Data Centres in order to reduce the TCO and increase the overall efficiency of the Data Centre.

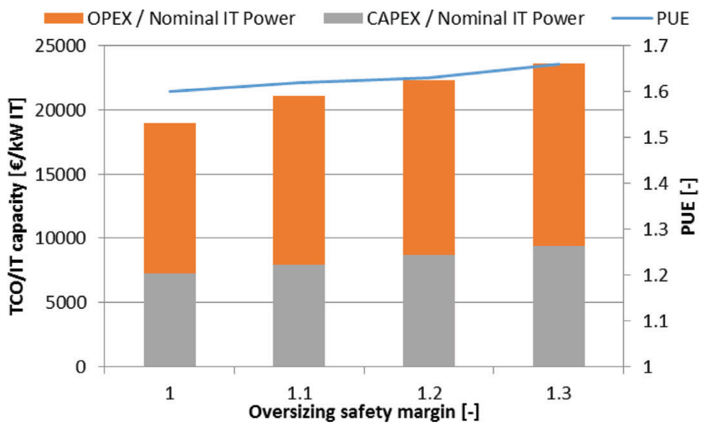


Figure 7.35 Total Cost of Ownership (CAPEX+OPEX) and PUE in function of the oversizing safety margin.

7.5 The RenewIT Tool

The RenewIT project developed a simulation tool to help Data Centre designers and operators to evaluate the energy performance of different combinations of renewable energy and efficiency measures solutions. The public RenewIT tool (www.renewit-tool.ue [6]) is a web-based planning tool to understand the costs and benefits-in economic, environmental and sustainability terms – of designing and operating a facility to use a high proportion of on-site and/or grid-based renewable energy. Therefore, the results of the tool can be used in pre-design phases and will help the industry (investors, operators, etc.) to take strategic decisions about energy efficiency strategies and renewables integration. Moreover, the RenewIT tool allows the users to analyse the benefit of implementing advanced strategies and renewables in different locations of Europe under different IT load workload and operational characteristics. The tool is built on top of advanced energy models, developed in TRNSYS. However, the RenewIT tool, as any other web application, needs to process the information as fast as possible in order to enhance the user experience. Therefore, it has been necessary to generate metamodels which are the computational core of the tool. Metamodels are simplified models generated by surface-response methods from the detailed dynamic models which runs with only key parameters already identified.

The Graphical User Interface (GUI) is divided in six different sections: general information, IT infrastructure, power and cooling characterization,

Figure 7.36 Home page of the RenewIT tool in www.renewit-tool.eu.

selected options and results page. Figure 7.37 shows an image of the different sections and the most relevant information requested in each stage. Behind the GUI there is the engine which processes the information introduced by the user combined with data from data bases and calculates the results for each scenario using the metamodels library.

7.6 Conclusion

Data Centres are very complex energy facilities which are influenced on one hand for the characteristics of the Data Centre such as type of IT load, cooling system, power distribution and on the other hand for boundary conditions such as location (weather and local energy resources and energy infrastructures availability), electricity price, etc. Therefore, dynamic energy modelling is necessary to predict energy and economic behaviour of these unique infrastructures.

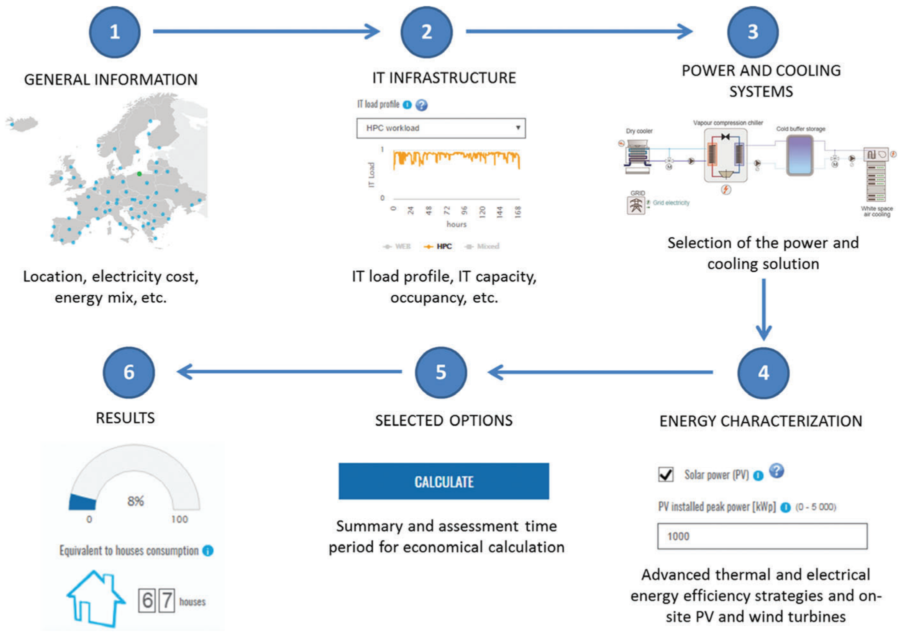


Figure 7.37 Scheme of the RenewIT tool functionality and layout.

This chapter provided a basic parametric analysis for each of the 6 concepts described varying some of the main parameters of each advanced solution. Concepts based on biogas CHP systems (with fuel cells or reciprocating engine) present promising numbers of PE_{nren} reduction but are not cost effective. The connection of a Data Centre to a district heating and cooling network while reusing the heat from liquid cooled servers is a very promising solution and cost effective. Using on-site PV or wind power production can be an interesting option towards Net Zero Energy Data Centres, but is dependent on the location.

The results shown and described in this chapter give enough information to know the influence of the variation of the main parameters of influence. However, it is needed to use detailed optimization and dynamic energy models together with information of local constraints, as energy prices or available space for renewables, to seek for a cost effective option and/or environmentally friendly solution.

References

[1] TRNSYS Thermal Energy System Specialists LLC , Version 17. [Online]. Available: http://www.trnsys.com/
[2] Wikipedia, "Köppen climate classification," 2015.
[3] CEN, "EN 15459 Energy performance of buildings – Economic evaluation procedure for energy systems in buildings," 2007.
[4] A. O. E. S. J. C. M. M. M. G. J. Carbó, "Experimental and numerical analysis for potential heat reuse in liquid cooled data centres," Energy Conversion and Management, vol. 112, pp. 135–145, 2016.
[5] Meteotest, "Meteonorm software v7," [Online]. Available: www.meteonorm.com. [Accessed 2017].
[6] "RenewIT tool," 2016. [Online]. Available: http://www.renewit-tool.eu/.
[7] IDAE, "CO2 emission factors," 2011.
[8] P. d. l'Alba. [Online]. Available: http://www.parcdelalba.cat. [Accessed 2017].