3

Environmental and Economic Metrics for Data Centres

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3.1 About Metrics in Data Centres

With escalating demand and rising energy prices, it is essential for the owners and operators of these mission-critical facilities to assess and improve Data Centre performance. Metrics are an important way to understand the economic and environmental impact of Data Centres and the results of applying energy efficiency measures or integrating renewable energy sources (RES). A wide range of energy-efficiency metrics and key performance indicators (KPIs) has been developed over the past years. In this framework, eight European projects with the common topic of energy efficiency in Data Centres have formed the Smart City Cluster Collaboration with the objective to define and to agree common metrics and methodologies. An official liaison has been established between the Smart City Cluster Collaboration with the join technical committee ISO/EIC JTC1-SC39 on "Sustainability for and by Information Technology" to collaborate in metrics standardisation activities.

Low-level measurement of operational variables such as temperature and relative humidity in Data Centre IT rooms are key aspects as they are part of the service-level agreements (SLA) in IT services. Several metrics addressing the issue if temperature and relative humidity are within the allowed boundaries are extensively described in the literature [38] and reviewed in the context of the [40]. Being aware of its relevancy, the focus of this chapter refers on metrics at facility level.

A diversity of views exits [13] about the convenience of using global synthetic indicators defined as a weighted combination of several basic metrics.

Other views prefer to show each metric separately supported with some graphic format. For example, a spider chart is able to provide a combined visualization of several metrics in one graph. The number of metrics (axes) may vary depending on the selection of metrics chosen by the Data Centre operator.

Figure 3.1 shows an example of a spider chart with 5 axes. Once the metrics are selected, it is also needed identifying a start and end point for each axis. In some cases, there are theoretical maximum and minimum values (e.g. share of renewables can only range from 0 to 1). In other cases, there are not clear maximum values (e.g. there is no maximum for PUE). Therefore, the axis ends will have to be established based on target values or other estimates. A spider chart using three axes is adopted by Future Facilities to define the ACE Performance Score [17], shown in Figure 3.2. The ACE Performance Score triangle compares the difference between the actual Data Centre's performance
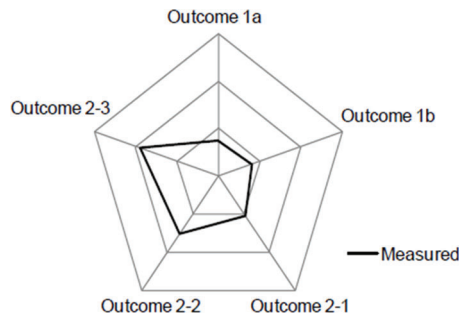
Figure 3.1   Example of generic spider chart for five metrics.
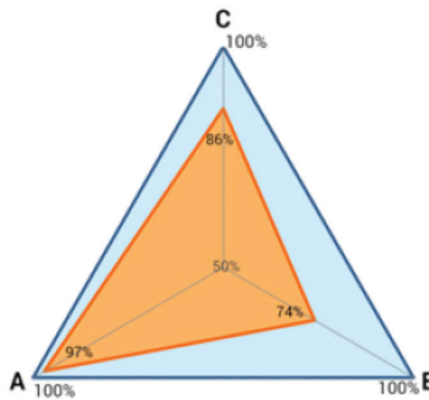
Figure 3.2   ACE Performance Score [17].

with the expected output when it was designed in three aspects: availability, capacity and efficiency.

Other companies are proposing different forms of dashboard to report key efficiency metrics for their companies. For example, Ebay implemented Digital Service Efficiency (DSE) methodology to see the full cost, performance and environmental impact of customer buy and sell transactions, giving eBay a holistic way to balance and tune its technical infrastructure [10]. A dashboard displays the Ebay's specific DSE measures over a set of user-selected time periods (see Figure 3.3).

A holistic framework helps the operator keep in mind the effects on all metrics simultaneously and is a way to grasp multiply metrics for Data Centre collectively [19]. Other important aspects that can influence energy metrics such as availability, capacity, economic costs or security issues in Data Centres can be also considered in a holistic perspective.

To assess the environmental impact of the Data Centres among other human-promoted activities is a key issue to assure the sustainability of our society and to prevent global warming effects. In the point of view of stakeholders responsible to take decisions about actions to carry out in Data Centres, and particularly related with implementation of measures to improve the energy efficiency and share of renewables, the economic feasibility must be included as one of the main indicators, including the costs of carbon emissions, if it is considered. This chapter proposes a methodology for cost-environmental analysis centred in energy use of Data Centres, aiming

Figure 3.3 Digital Service Efficiency (DSE) dashboard from [10].

to analyse both the economic and environmental impact of any efficiency measure. This will allow to optimize and to select the optimal solution among several options. This comparative framework needs to be based on relevant metrics, both environmental and financial, which are described in Section 3.3 of this chapter. Moreover, other relevant energy-efficiency metrics or KPI's to characterise the use of renewables in Data Centres are introduced as well.

3.2 Data Centre Boundaries for Metrics Calculation

3.2.1 Definition of Boundaries

In a future perspective of energy-producing premises, relying on renewable energy sources or high-efficient systems, the Data Centre infrastructure can be categorized with different system blocks, as shown in Figure 3.4.
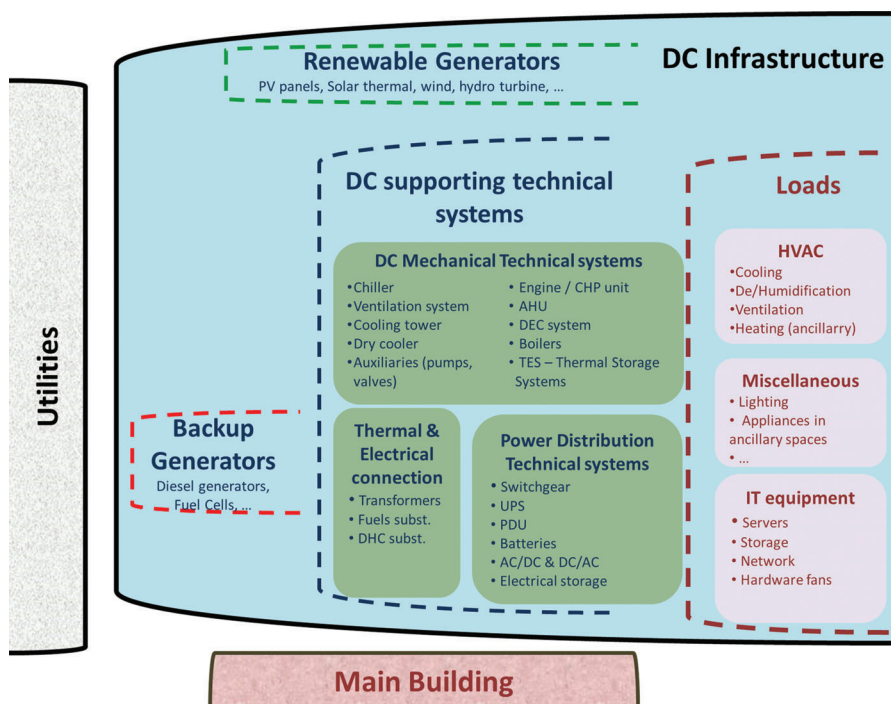

Figure 3.4 Main boundaries in a Data Centre for the assessment of metrics [50]. *Source:* IREC.

- Data Centreloads
    - IT workload (IT equipment)
    - Miscellaneous loads (i.e.lighting)
    - Mechanical or HVAC load (i.e. refrigeration for white space and ancillary spaces)
- Data Centre supporting technical systems
    - Power distribution systems. Systems which distribute power to IT equipment and other elements in the Data Centre.
    - Mechanical systems. Components as chillers, CRAC, air handling units, pumps, cooling towers, etc., aiming to cover HVAC needs.
    - Technical connection subsystems. Systems for connecting with electrical and thermal utilities as for example the power transformers to connect to the main grid or the heat exchangers and additional hydraulic elements to connect with a district cooling network.
- On-site renewable energy generators, which are renewable energy systems placed in the Data Centre footprint, as for example photovoltaic (PV) panels or micro-wind turbines.
- Backup system. Component to supply power in case that the electricity grid presents a problem, as diesel generators, batteries, fuelcells or flywheels.

3.2.2 Energy Flows

In a so-called Net Zero Energy Data Centre, highly efficient and renewable sources driven on-site energy supply systems will be adopted, such as cogeneration units, PV panels or solar thermal collectors. Thereby, a wider group of technologies is interposed between the local utilities networks from which the driven energy carriers are imported, like gas for a cogeneration unit, and the equipment which receive the energy from the supply systems before feeding it into the IT equipment. Such technologies can support the Data Centre operation by supplying electricity but also heat for cooling purposes, like in the case of tri-generation or solar cooling systems.

Some of the energy supply systems or heat recovering systems from the IT equipment, all of them being part of the Data Centre infrastructure, can export energy to the utility or can be shared with the main building where the Data Centre is installed. Figure 3.5 shows a simplified scheme where backup generators have been eliminated from the scheme and energy flows have been divided in different energy carriers. The scheme is simplified eliminating
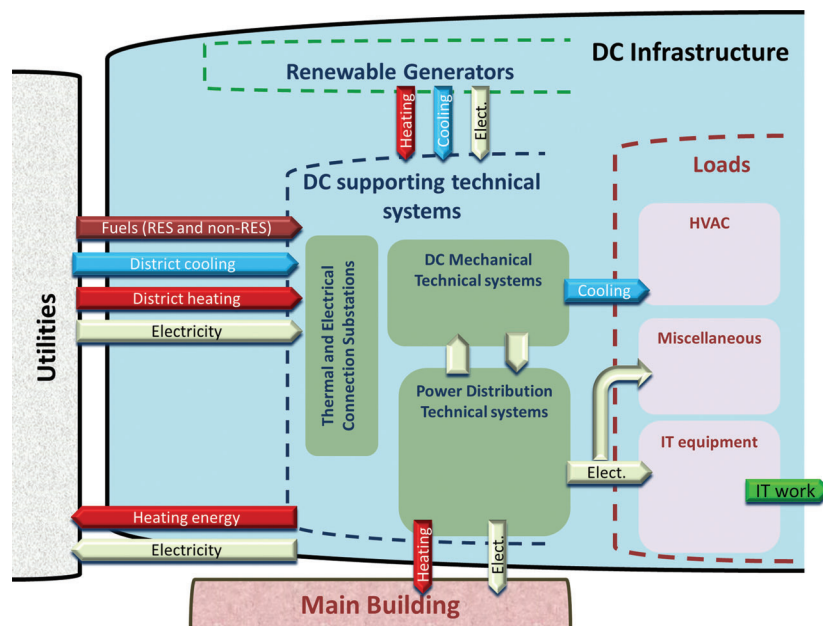
Figure 3.5 Simplified scheme of energy flows in a Data Centre infrastructure with electricity and cooling energy needs [50]. *Source:* IREC.

the energy flows which are less relevant for a Data Centre. Only electricity and cooling needs are considered, although in some Data Centre infrastructures, some heating loads could be required for ancillary spaces. Regarding exported energy, Data Centre exports of cooling to the utilities or other buildings is not considered, as it is an intensive cooling consumer.

Delivered and exported energies have to be calculated separately for each energy carrier. Delivered energy from outside the Data Centre infrastructure can be in the form of electricity, heating or cooling from a district net-work or fuels, both renewable and non-renewable. On-site renewable energy generators without fuels mean the electric and thermal energy (heating or cooling) produced by solar collectors, PV, wind or hydro turbines. The thermal energy extracted from ambient or other renewable environments (e.g. sea water) through heat exchangers is also considered on-site renewable energy. Renewable fuels, as for example biomass or biogas, are not included in on-site renewables, but they are taken into account as renewable part of the delivered energy, in form of renewable fuel. Figure 3.6 depicts the nomenclature of the energy flows used in this book in a simplified way.
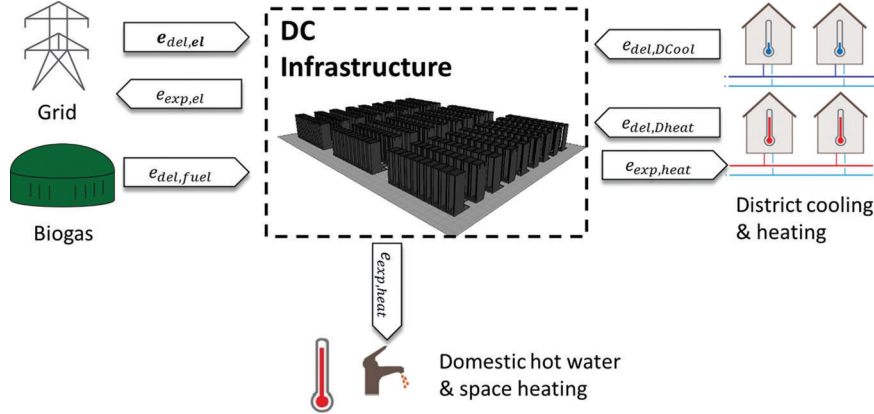
Figure 3.6 Simplified scheme of energy flows in a Data Centre infrastructure with nomenclature.

3.3 Metrics for Cost-Environmental Analysis

3.3.1 Environmental Impact Metrics

3.3.1.1 Data Centre primary energy

The main metric to evaluate the energy consumption in the Data Centre considering environmental issues is the Data Centre primary energy. The Data Centre primary energy accounts for the energy that has not been subjected to any conversion of transformation process which also receives the name of source energy, as for example in [19].

The primary energy indicator sums up all delivered and exported energy, for all the energy carriers, into a single indicator with corresponding (national, regional or local) primary energy weighting factors. By default, the non-renewable Data Centre primary energy is used. For a given energy carrier, the non-renewable primary energy factor is the non-renewable primary energy divided by delivered energy. The non-renewable primary energy is defined as the energy required to supply one unit of delivered energy, taking into account of the non-renewable energy required for extraction, processing, storage, transport, generation, transformation, transmission, distribution and any other operations necessary for delivery to the Data Centre in which the delivered energy will be used. Notice that the non-renewable primary energy factor can be less than unity if renewable energy has been used.

$$PE_{\text{DC,nren}} = \int Pe_{\text{DC,nren}}(t) \cdot \mathrm{d}t \qquad (3.1)$$

$$Pe_{\text{DC,nren}}(t) = \sum_i (e_{\text{del},i}(t) \cdot w_{\text{del,nren},i}(t)) - \sum_i (e_{\text{exp},i}(t) \cdot w_{\text{exp,nren},i}(t))$$
(3.2)

If we consider the energy flows which are common in a Data Centre according to Figure 3.6 (excluding cooling as exported energy option), primary energy can be calculated using Equation (3.3)[1].

$$\begin{aligned}
Pe_{\text{DC,nren}} = &\; [(e_{\text{del,el}} \cdot w_{\text{del,nren,el}}) + (e_{\text{del,fuel}} \cdot w_{\text{del,nren,fuel}}) + \\
&+ (e_{\text{del,DHeat}} \cdot w_{\text{del,nren,DHeat}}) + (e_{\text{del,DCool}} \cdot w_{\text{del,nren,DCool}})] - \\
&- [(e_{\text{exp,el}} \cdot w_{\text{exp,nren,el}}) + (e_{\text{exp,heat}} \cdot w_{\text{exp,nren,heat}})]
\end{aligned}$$
(3.3)

According to this definition, Net Zero Energy Data Centre has an exact performance level of 0 kW·$h_{\text{PE,nren}}$ non-renewable primary energy. A plus energy or positive energy Data Centre will have a negative value (<0) of non-renewable primary energy.

In some cases, instead of using the non-renewable energy factors, the total energy weighting factors may be used. In this case, the total Data Centre Primary Energy is the one that accounts both for the non-renewable and renewable primary energy. The total primary energy factors always are equal or exceed 1.0.

$$PE_{\text{DC,tot}} = \int Pe_{\text{DC,tot}}(t) \cdot \mathrm{d}t$$
(3.4)

$$Pe_{\text{DC,tot}}(t) = \sum_i (e_{\text{del,i}}(t) \cdot w_{\text{del,tot,i}}(t)) - \sum_i (e_{\text{exp,i}}(t) \cdot w_{\text{exp,tot,i}}(t))$$
(3.5)

Remarks on Weighting Factors

Quantification of proper conversion factors is not an easy task, especially for electricity and thermal networks as it depends on several considerations, e.g., the mix of energy sources within certain geographical boundaries (international, national, regional or local), average or marginal production, present or expected future values and so on. In general, there are no correct conversion factors in absolute terms. Rather, different conversion factors are possible, depending on the scope and the assumptions of the analysis. This leads to the fact that "strategic corrected" weighting factors may be adopted in order to find a compromise agreement.

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[1]Notice that matemathical formulation has been simplified. All the terms are time dependent.

Furthermore, "strategic factors" may be used in order to include considerations not directly connected with the conversion of primary sources into energy carriers. Strategic factors can be used to promote or discourage the adoption of certain technologies and energy carriers, as it has been proven in [29] for the case of Net Zero Energy Buildings.

Generally speaking, weighting factors can be generally time dependent, as the share of renewables is dependent on the season and the period of the day. In [18], the seasonal and daily variation of conversion factors for the electricity mix in several European countries has been analysed. However, they are subjected to changes due to the planned increase in the share of renewables towards 2050. Usually, mean annual national and regional factors are available subjected to different regional or country approaches [35]. In case of absence of national/regional factors, European or global factors can be used as reference. The FprEN ISO 52000-1:2016 [8] proposes default values for primary energy weighting factors which can be used for reference. In [19], global average factors are provided and its use is recommended for comparison across different regions in the world.

Remarks on Exported Energy Accounting

One key aspect that affects the computation of the defined Data Centre primary energy metrics is the methodology for accounting the exported energy which is the delivered energy by technical Data Centre systems through the boundary and used outside the Data Centre boundary. Generally speaking, the exported energy can be both in forms of electricity or thermal energy (heating and cooling). It accounts for the energy generated on-site which do not match instantaneously the energy needs and therefore needs to be exported. By default, the weighting factors for the exported energy for energy carrier are equal to the factor for the delivered energy, if not specifically defined in other way. However, the factors to apply to the exported energy are not completely clear defined. FprEN ISO 52000-1:2016 proposes different factors for the electricity depending if it is exported to the grid, exported for the immediate use or exported temporary to be reused later, but no proposal for heat or cooling exported flows is presented. In a Data Centre, excess heat could be from a cogeneration system or from the ability to re-use heat from the IT white space. Recommendation by the German Heat and Power Association (AGFW) [3] is to consider $w_{\text{exp,nren,heat}} = 0.0$ because the Data Centre waste heat is a by-product of a process which is not related to the power supply

industry. In calculations in Chapter 7, by default $w_{\text{exp,nren,heat}}$ has a value different from zero as considered the amount of heat that can be effectively used by a third entity in the primary energy balance.

3.3.1.2 Data Centre CO$_2$ emissions

Data Centre CO$_2$ emissions can be computed using adequate conversion factors for each energy carrier, using similar methodology that used to compute Data Centre primary energy. The weighting factors to be used are the CO$_2$ emission coefficient which is the quantity of CO$_2$ emitted to the atmosphere per unit of energy, for a given energy carrier. The CO$_2$ emission weighting factor can also include the equivalent emissions of other greenhouse gases. See [18] about CO$_2$ emission coefficients from the electricity grid.

$$EM_{\text{DC,CO}_2} = \int em_{\text{DC,CO}_2}(t) \cdot \mathrm{d}t \tag{3.6}$$

$$em_{\text{DC,CO}_2}(t) = \sum_i (e_{\text{del,i}}(t) \cdot w_{\text{del,CO}_2,\text{i}}(t)) - \sum_i (e_{\text{exp,i}}(t) \cdot w_{\text{exp,CO}_2,\text{i}}(t)) \tag{3.7}$$

3.3.1.3 Data Centre water consumption

Depending on the design of the cooling system of Data Centres, they can require significant amounts of water which have to be accounted for, especially if Data Centre is located in a site with limited availability of water. Then, the water consumption is a valued that needs to be considered which can be measured continuously or integrated over a period of time using Equation (3.8) (Water$_{\text{DC}}$).

$$\text{Water}_{\text{DC}} = \int \text{water}_{\text{DC}}(t) \cdot \mathrm{d}t \tag{3.8}$$

3.3.2 Financial Metrics

3.3.2.1 Methodological reference framework

A methodology framework is proposed which gives the basis to consider calculation of cost-optimal levels for both financial and macroeconomic viewpoint. The methodological framework is adapted from the existing *EN-15459* [7], together with [12, 14]. In the financial calculation, the relevant prices to take into account are the prices paid by the end-user

(Data Centre owner or operator) including all applicable taxes and charges. For the calculation at macroeconomic level, an additional cost category taken into account the costs of greenhouse gas emissions is introduced and applicable charges and taxes should be excluded.

3.3.2.2 Global cost

The total cost of ownership (TCO) (or the total global cost) is defined as the present value of the initial investment costs (CAPEX), sum of running costs or operational expenditures (OPEX), and replacement costs (referred to the starting year), as well as residual values, if applicable. Thus, it can be understood as a way to quantify the financial impact of any capital investment regarding IT business (see Figure 3.7). The TCO is used to assess the true total costs of building, owning and operating a Data Centre physical facilities [45]. The basic principle for the calculation of the global cost is made for the system – or each component j of the system – considering the initial investment C_I, the present value of annual costs for any year i
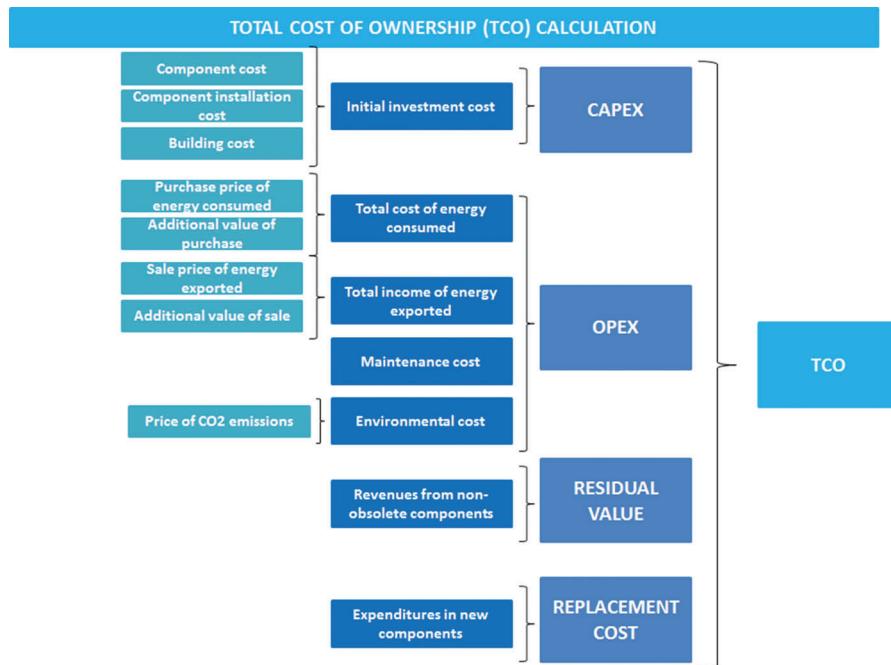

Figure 3.7 Scheme about the different parts composing the Total Cost of Ownership (TCO).

and the final value of any component or system. General expression for the calculation of the global cost for a period τ is Equation (3.9).

$$\text{TCO}\,(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}\,(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \qquad (3.9)$$

where

C_I are the initial investment costs or CAPEX

$C_{a,i}\,(j)$ are the annual costs for the year i and component j, including operational and replacement costs, namely OPEX

$R_d(i)$ is the discount rate for the year i

$V_{f,\tau}(j)$ is the final value of component j, if any, at the end of the period.

3.3.2.3 CAPEX: capital expenditure

This is the amount of money used to acquire assets or improve the useful life of existing assets. In general terms, CAPEX would include server purchasing costs, construction costs of a new Data Centre and any investment realized to improve or enlarge the Data Centre facility. Market survey developed by [2] in 2012 estimates the investment costs for a traditional Data Centre and for modular Data Centres. The average values in € per unit of IT installed capacity power are 10 784 €/kW and 6 470 €/kW for traditional and modular Data Centres, respectively.

$$\text{CAPEX} = \sum_{j=1}^{NC} [\text{CC}_j + \text{CI}_j] + \text{CCDC} \qquad (3.10)$$

where

NC are the number of components defining the energy facility

CC_j is the investment cost of component j

CI_j is the installation cost of component j

CCDC is the cost of the main building the Data Centre, mainly building cost.

3.3.2.4 OPEX: operating expenditure

Operating expenditure (OPEX) is the ongoing cost for running a product, business or system. In the case of Data Centres, OPEX (see Equation (3.11)) includes [4] the following:

- Energy costs: electricity costs and other energy carrier costs
- License costs
- Maintenance costs
- Labour costs
- Utilities costs, except energy cost
- Replacement cost

Energy costs should be calculated for each energy carrier and prices can be temporary dependent. The costs of energy consumed for a given period of time can be calculated with Equation (3.12) being the weighting factors the economic cost per unit of delivered energy or the income per unit of exported energy.

$$\text{OPEX} = \text{OPEX}_{\text{EC}} + \text{OPEX}_{\text{CM}} + \text{OPEX}_{\text{REC}} + \text{OPEX}_{\text{CO}_2} \quad (3.11)$$

$$\text{OPEX}_{\text{EC}} = \int Ce_{\text{DC}}(t) \cdot \text{d}t = \int \sum_i (e_{\text{del,i}} \cdot w_{\text{del},\text{€},\text{i}})$$

$$- \sum_i (e_{\text{exp,i}} \cdot w_{\text{exp},\text{€},\text{i}}) \quad (3.12)$$

$$Ce_{\text{DC}}(t) = \sum_i (e_{\text{del,i}}(t) \cdot w_{\text{del},\text{€},\text{i}}(t)) - \sum_i (e_{\text{exp,i}}(t) \cdot w_{\text{exp},\text{€},\text{i}}(t))$$

One should consider as negative expenses, additional economic incomes derived, for example, from energy management actions or better management of available capacity.

3.3.3 Cost-Efficiency Analysis

Cost-efficiency analysis can be done by establishing a comparative methodology framework. The methodology specifies how to compare energy-efficiency measures, measures incorporating renewable energy sources and packages of such measures in relation to their environmental performance and the cost attributed to their implementation.

In order to have an appropriate evaluation among a set of solutions, one could opt for a graphical representation. The x-axis represents the Data Centre primary energy or other environmental index (CO_2 emissions or water consumption) and the y-axis the TCO. Each point represents the values (TCO and $PE_{\text{DC,nren}}$) that result when a combination of compatible energy efficiency and energy supply measures is applied to a Data Centre.
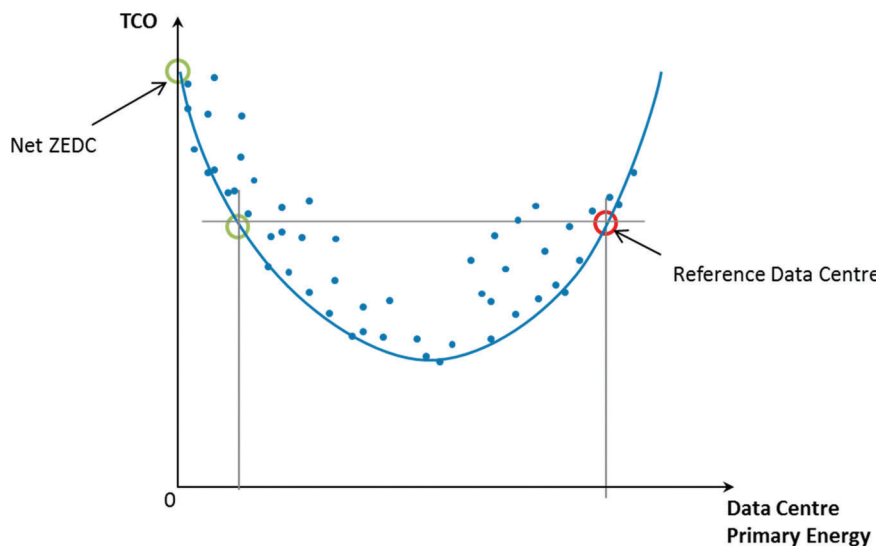
Figure 3.8 Graphical representation for cost-optimal analysis. *Source:* IREC.

If cost-effective measure is applied to a reference Data Centre and primary energy is used as environmental index (each point in Figure 3.8 represents a solution), it is possible to identify the following:

- The cost-optimal configuration. The solution having the minimum global cost.
- A set of solution which are cost effective. The ones having less primary energy and equal or less TCO than the reference case.
- The additional global cost needed to reach a Net Zero Energy Data Centre.

3.4 Energy Efficiency and Renewable Energy Metrics

3.4.1 Power Usage Effectiveness (PUE)

Power usage effectiveness, known as PUE, is the most popular and well-known key performance indicator used in the Data Centre industry which aims to quantify the efficient use of energy in the form of electricity. PUE is defined as ratio of the Data Centre total energy consumption to information technology equipment energy consumption, calculated, measured or assessed across the same period. The reader is referred to the standard ISO/IEC 30134-2:2016 Information Technology – Data Centres – Key Performance Indicators – Part 2:

Power usage effectiveness (PUE) to know more details about the categories of PUE and the instructions for its measurement. Due to the heterogeneity of Data Centre facilities, it is not recommended that PUE values from different Data Centres are compared directly. PUE should principally be used to assess trends in an individual facility over time and to determine the effects of different design and operational decisions within a specific facility [23]. In the framework of this book, advanced resolution of PUE (Category 3 – PUE$_3$) is used. PUE$_3$ is characterized by the measurement of the IT load at the IT equipment in the Data Centre.

As a result that several energy carriers can be used to determine the total energy consumed for the Data Centre operation, here PUE is calculated as the total primary energy consumption of the Data Centre (PE$_{DC,tot}$) divided by the total primary energy delivered to the IT equipment (PE$_{DC,tot,IT}$). PUE is a metric to identify how efficient the electricity is used from the Data Centre control to the IT equipment. Therefore, it gives the relation of the extra amount of energy consumed in order to keep the servers working properly. PUE is defined in coherence with the standard [23] where the energy that is reused is not subtracted from the total.

$$\text{PUE} = \frac{PE_{\text{DC,tot}}}{PE_{\text{DC,tot,IT}}} = \frac{\int Pe_{\text{DC,tot}}(t) \cdot \mathrm{d}t}{\int Pe_{\text{DC,tot,IT}}(t) \cdot \mathrm{d}t}$$

where

$$Pe_{\text{DC,tot}}(t) = \sum_i e_{\text{del,i}}(t) \cdot w_{\text{del,tot,i}}(t) - \sum_i e_{\text{exp,el}}(t) \cdot w_{\text{exp,tot,el}}(t) + \\ + e_{\text{ren,i}}(t) \cdot w_{\text{del,tot,i}}(t)$$

$$Pe_{\text{DC,tot,IT}}(t) = e_{\text{del,IT}}(t) \cdot w_{\text{tot,IT}}(t)$$

$$w_{\text{tot,IT}} = \frac{\text{Primary energy to produce electricity} + \text{Purchased electricity}}{\text{All electricity at site}}$$

$$w_{\text{tot,el}} = \frac{e_{\text{del,i}} \cdot w_{\text{del,tot,i}} + e_{\text{grid}} \cdot w_{\text{del,tot,el}}}{e_{\text{del,i}} + e_{\text{grid}}}$$

3.4.2 Renewable Energy Ratio

The renewable energy ratio (RER) is the metric that allows calculating the share of renewable energy use in a Data Centre. The renewable energy ratio is calculated relative to all energy use in the Data Centre, in terms of total primary energy and it is analogous to the Total PE Percent described in [39] and [31].

$$\mathrm{RER_{EP}} = \frac{\sum_i e_{\mathrm{ren,i}} + \sum_i [(w_{\mathrm{del,tot,i}} - w_{\mathrm{del,nren,i}}) \cdot e_{\mathrm{del,i}}]}{\sum_i e_{\mathrm{ren,i}} + \sum_i (w_{\mathrm{del,tot,i}} \cdot e_{\mathrm{del,i}}) - \sum_i (w_{\mathrm{exp,tot,i}} \cdot e_{\mathrm{exp,i}})}$$
(3.13)

The calculation considers that exported energy compensates delivered energy. By default, it is considered that exported energy weighting factors compensate the electrical grid mix or the district heating or cooling network mix, if any, in the case of thermal energy. Regarding consideration of exported energy in the computation, the reader is referred to the remarks in Section 3.1.1.

For the calculation of the RER, all renewable energy sources have to be accounted for. These include solar thermal, solar electricity, wind and hydroelectricity, renewable energy captured from ambient heat sources by heat pumps and free cooling, renewable fuels and off-site renewable energy. For on-site renewable energy, the total primary energy is 1.0. The amount of energy captured by heat pumps from ambient heat sources should be according EU Directive 2009/28/EC and Commission Decision 2013/114/UE [11]. Figure 3.9 depicts the boundaries for the energy use system and the main flows that need to be considered to compute RER.
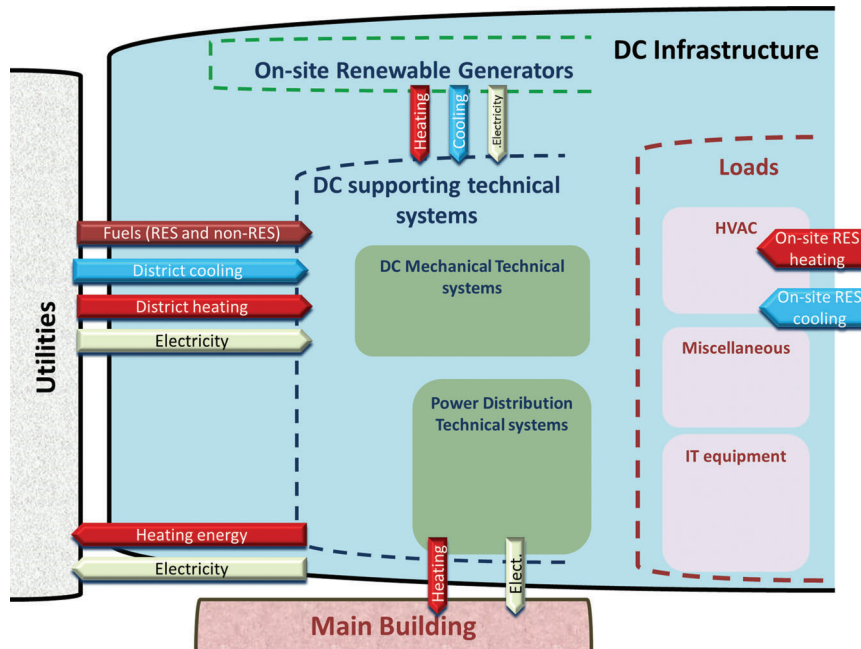

Figure 3.9 Use system boundary for renewable energy ratio (RER) calculation.

3.4.3 Renewable Energy Factor

In contrast to renewable energy ratio (RER) as defined in previous section, other KPI is commonly used to characterise the percentage of renewable energy over total Data Centre energy. The reader is referred to the standard ISO/IEC 30134-2:2016 Information Technology – Data Centres – Key Performance Indicators – Part 3: Renewable energy factor (REF) to know more about the computation of the REF. Main difference between the RER is that REF shall have a maximum value of 1.0, as on-site generation of renewable energy beyond the need of the Data Centre should not be accounted for REF calculations. In addition, only the renewable energy that is owned and controlled by the Data Centre is accounted, meaning that the energy for which the Data Centre owns the legal right, as it is certified by providers or renewable energy certificates. On-site generation which certificates are sold together with the generated energy must not be taken into account for the REF calculation. Using the same nomenclature, REF can be formulated as follows:

$$\text{REF}_{\text{EP}} = \frac{\sum_i e_{\text{ren,i}} + \sum_i [(w_{\text{del,tot,i}} - w_{\text{del,nren,i}}) \cdot e_{\text{del,i}}]}{\sum_i e_{\text{ren,i}} + \sum_i (w_{\text{del,tot,i}} \cdot e_{\text{del,i}})} \tag{3.14}$$

3.5 Capacity Metrics

3.5.1 Introduction

Data Centres are planned and designed to meet the maximum future estimated capacity for the IT requirements in a period of time (up to 10 years, usually). This means that at day one, the investments usually donot fulfil the ultimately design capacity and this is expected to increase from the start-up load to the expected final value. The unused capacity in IT and power infrastructures represents avoidable capital costs and operational costs, including maintenance and energy costs, too. According to several sources, the degree of utilisation of Data Centres is between 50% [30] and 70% [17]. Many operators have the standard practice of utilizing only a fraction, such as 80% or 90% of the installed capacity [30], assuming that operating the system at less than full power will maximize overall reliability. The traditional model for planning Data Centres infrastructures is illustrated in Figure 3.10 which depicts the waste of resources to oversizing. Deploying an adaptable physical infrastructure, the waste due to oversizing can be reduced, as it is shown graphically in Figure 3.11.
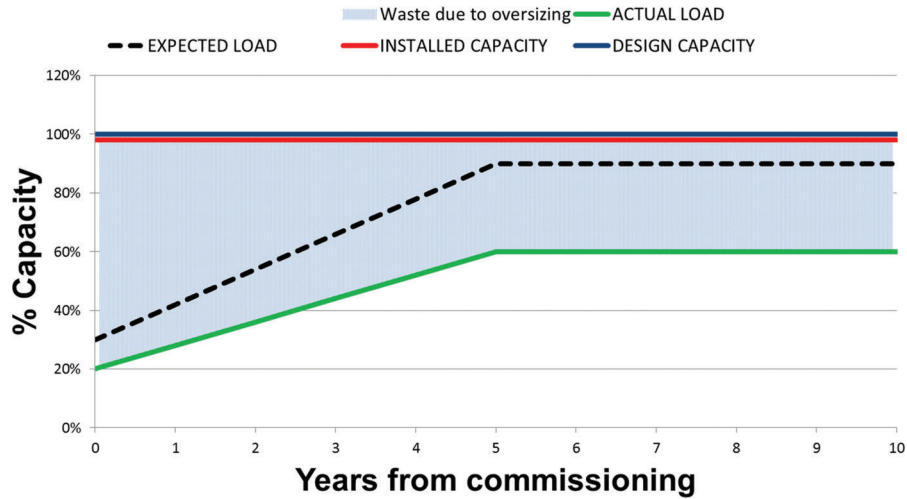
Figure 3.10   Design capacity and expected load in a planning model with all the capacity available since day one. Adapted from [30].
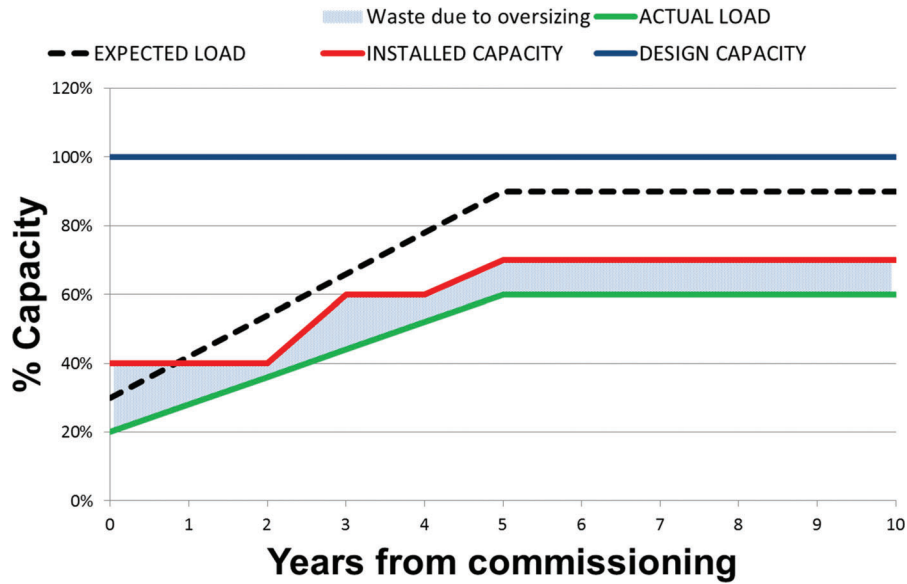

Figure 3.11   Design capacity and expected load in a planning model with an adaptable physical infrastructure. Adapted from [30].

Then, having in mind that unused capacities have a big impact in the use of resources and in the economic profitability of a Data Centre, some metrics have been recently proposed to show the utilization of the available capacity and the capacity analysis starts to be introduced in DCIM. ACE score [17] shows the utilization of capacity but it is referred to the IT load Capacity. A capacity metric, named the Cooling Capacity Factor (CCF) is presented in [5]. The CCF is defined as the ratio of total running manufacturer's rated cooling capacity to 110% of the critical load. Ten percent is added to the critical load to estimate the additional heat load of lights, people, etc. The white paper [5] reveals average CCF of 3.9, which is very high compared to the ideal CCF = 1.2.

Therefore, capacity metrics intends to relate the actual peak IT power and the peak facility power with both the design and installed capacity, in case they are different. With these metrics, one can evaluate how to increase as much physical capacity in a Data Centre as possible (this is the capacity that owner–operator has already paid for). Failing to use this capacity will incur future capital and operational expenditure. In case of Data Centres incorporating renewable energy systems, the on-site generation system is also characterized by its capacity. Also, we can distinguish between the design capacity, meaning the ultimately generation capacity related with the design load, the actual installed capacity and the actual peak power of the generation system. Having in mind that generation power can be instantaneously higher than the load, this leads to the situation of exporting energy to the grid.

3.5.2 Capacity Metrics

The *connection capacity credit*, or *power reduction potential* [34], is defined as the percentage of grid connection capacity that could be saved compared to a reference case. Positive values of this index indicate a saving potential; negative values indicate a need to increase the grid connection capacity with respect to the reference case. It can be formulated in the Equation (3.15).

$$CC = 1 - (DR/DR_{ref}) \qquad (3.15)$$

Based on that concept, some capacity credit (CC) metrics are proposed for Data Centres, both focusing in the IT capacity and the total facility capacity. Notice that in the following proposed metrics, it is assumed that the actual facility peak power is greater than the generation peak power. If not, dimensioning rate (DR) should be used and some of the equations will need to be reformulated using DR.

IT Installed Capacity Credit

$$\mathrm{CC_{IT,inst}} = 1 - (P_{\mathrm{IT}}/P_{\mathrm{IT,inst}}) \tag{3.16}$$

IT installed Versus Designed Capacity Credit

$$\mathrm{CC_{IT,des}} = 1 - (P_{\mathrm{IT,inst}}/P_{\mathrm{IT,des}}). \tag{3.17}$$

Total Facility Installed Capacity Credit

$$\mathrm{CC_{fac,inst}} = 1 - (P_{\mathrm{fac}}/P_{\mathrm{fac,inst}}) \tag{3.18}$$

Total facility Installed Versus Designed Capacity Credit

$$\mathrm{CC_{fac,des}} = 1 - (P_{\mathrm{fac,inst}}/P_{\mathrm{fac,des}}) \tag{3.19}$$

where

$P_{\mathrm{IT,des}}$ Designed IT power capacity
$P_{\mathrm{IT,inst}}$ Installed IT power capacity
P_{IT} Actual IT peak power
$P_{\mathrm{fac,des}}$ Designed total facility power capacity
$P_{\mathrm{fac,inst}}$ Installed total facility power capacity
P_{fac} Actual total facility peak power

Space Capacity Credit

However, the physical capacity is dictated by the resource that is least available which could be space rather than cooling or IT power. Then, we can define an additional capacity metric related to the surface used, the so-called space capacity credit.

$$\mathrm{CC_{IT,m2}} = 1 - \left(\frac{\text{Actual whitespace m}^2 \text{ occupied}}{\text{Design withespace m}^2} \right)$$

3.6 Examples

In this section, some illustrative examples have been provided to demonstrate the calculation of metrics for several Data Centre designs. Data Centre concepts presented in each example and the numerical values for each of the energy flows are based in rough annual calculations and estimations. For each of the examples, electrical and thermal schemes of the concept are presented together with a Sankey diagram to show the energy flows in the Data Centre. The primary energy factors and CO_2 emission factor used to calculate the metrics in the different examples are listed in Tables 3.1 and 3.2.

Table 3.1 Primary energy factors of the examples

		Primary Energy Factor (w)	Example 1	Example 2
Delivered	Non-Renewable	Electricity	2.135	2.135
		Biogas	–	–
		District Cooling	–	0.2
		On-site PV	0.0	–
		Aerothermal	0.0	0.0
	Total	Electricity	2.461	2.461
		Biogas	–	–
		District Cooling	–	1
		On-site PV	1.0	–
		Aero thermal	1.0	1.0
Exported	Non-Renewable	Electricity	2.135	2.135
		Heat	–	1.0
		District Cooling	–	0.2
	Total	Electricity	2.461	–
		Heat	–	1.0

Table 3.2 CO_2 emission factor of the examples

		CO_2 emission Factor (w)	Example 1	Example 2
Delivered $\frac{kg_{CO_2}}{kWh_{el}}$	CO_2	Electricity	0.348	0.348
		Biogas	–	–
		District Cooling	–	0
Exported $\frac{kg_{CO_2}}{kWh_{el}}$	CO_2	Electricity	0.348	0.348
		Biogas	–	–
		District Cooling	–	0

3.6.1 Example 1. PV System and Ice Storage

Example 1 corresponds to a concept where a vapour-compression chiller with wet cooling towers is used to produce cooling energy during summer. The electrical power required to drive the chiller can be purchased from the grid or generated by the photovoltaic system on the Data Centre footprint. A large ice storage tank is used for decoupling power and cooling generation from cooling demand (Figures 3.12 and 3.13).

Main Parameters of the System

The system uses a PV plant to satisfy approximately 80% of the energy consumption of the Data Centre. One part of the electricity generated by the PV panels is not self-consumed and therefore exported to the grid.
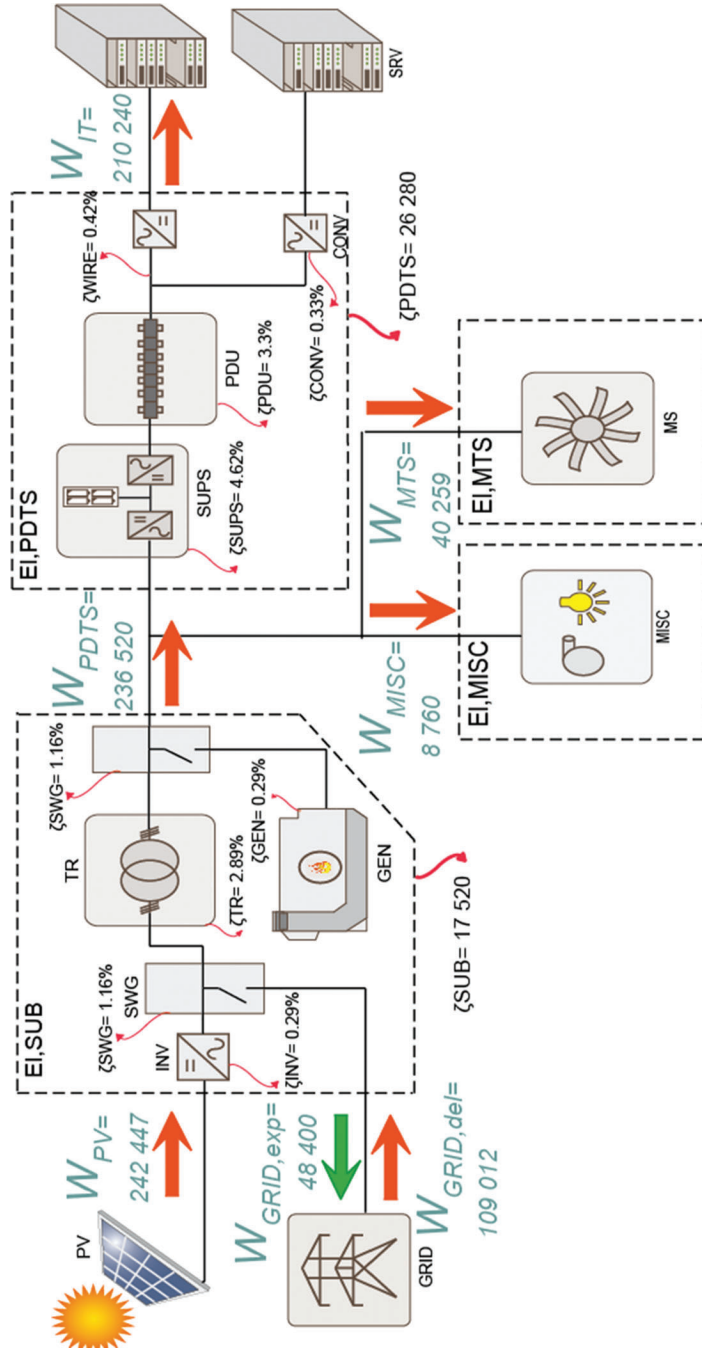
Figure 3.12   Example 1: PV system and ice storage, electrical scheme and main electricity flows.
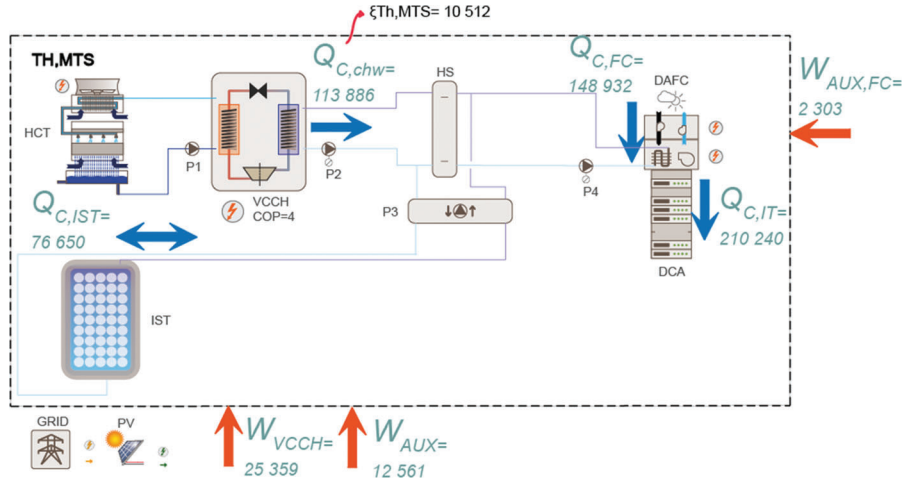
Figure 3.13 Example 1: PV system and ice storage, thermal scheme and main thermal and electricity flows linked to the mechanical technical systems.

The hypotheses for the facility power capacities are that the installed capacity is 20% higher than peak power value and the design capacity is the same as the installed capacity. As the example is located in Barcelona, it is assumed that the free cooling strategy is applied during 5374 hours. SEER values of 4.0 and 70.0 are assumed for the performance of the VCCH and the free cooling, respectively (Figure 3.14 and Table 3.3).

$$P_{IT} = 24 \text{ kW} \quad P_{fac,G=0} = 41.2 \text{ kW} \quad P_{PV} = 174 \text{ kW}$$

$$P_{IT,inst} = 1.2 \cdot P_{IT} = 28.8 \text{ kW}_{el}, P_{fac,inst} = 1.2 \cdot P_{fac} = 1.2 \cdot 144 = 172.8 \text{ kW}_{el}$$

$$P_{IT,des} = 1.1 \cdot P_{IT,inst} = 31.7 \text{ kW}_{el}, P_{fac,des} = 1.0 \cdot P_{fac,inst} = 172.8 \text{ kW}_{el}$$

$$\text{SEER}_{VCCH} = 4.0 \quad \text{SEER}_{FC} = 70$$

$$W_{IT} = 210240 \text{ kWh}$$

$$Q_{C,FC} = 161220 \text{ kWh}_{th}$$

$$Q_{C,chw} = (Q_{C,IT} - Q_{C,FC}) + \xi_{th,MTS} = (210240 - 161220) + 52560$$
$$= 101580 \text{ kWh}_{th}$$

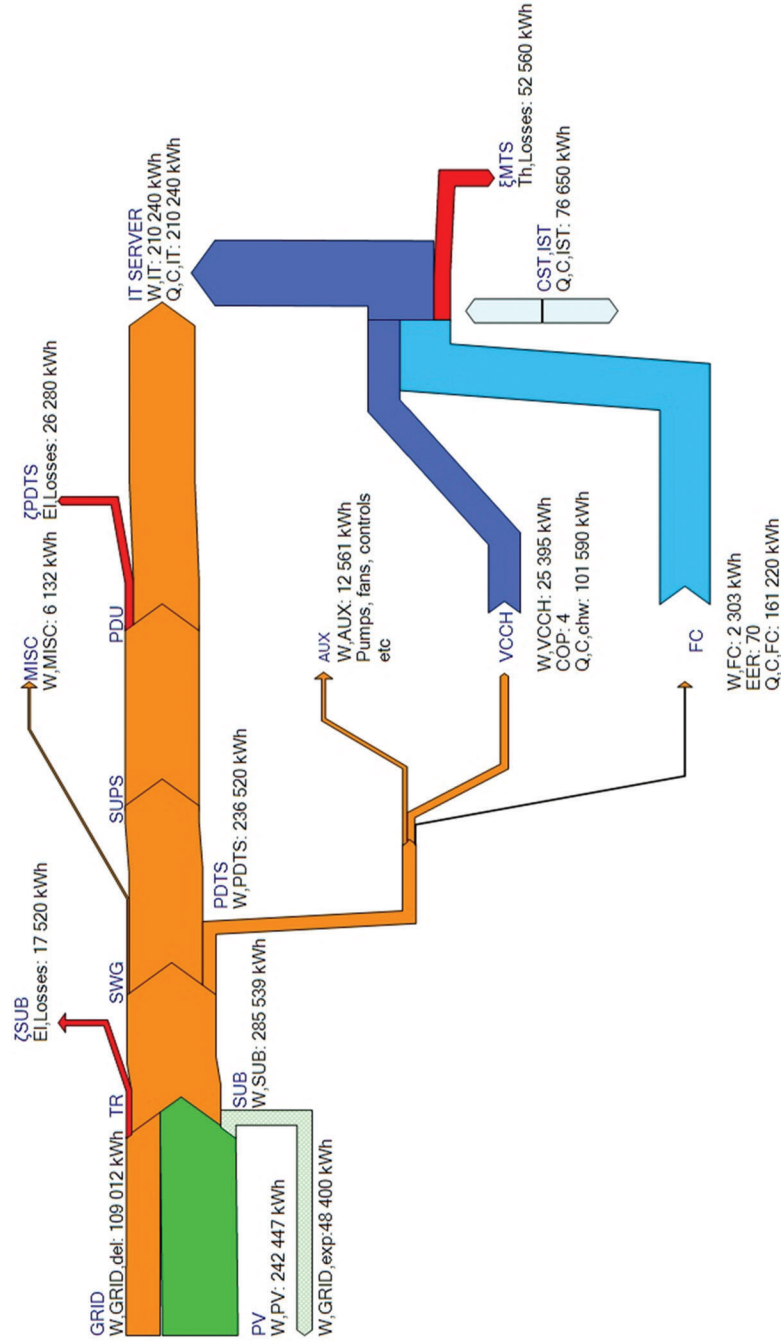$$W_{VCCH} = \frac{Q_{C,chw}}{\text{SEER}} = \frac{101580}{4.0} = 25395 \text{ kWh}_{el}$$

Figure 3.14   Example 1: PV system and ice storage. Sankey diagram.

Table 3.3 Example 1. Summary table of main energy flows

Symbol	Definition	kWh/year	PE nren	PE ren	PE tot
$W_{\mathrm{GRID,del}}$	Delivered grid electricity	109 012	232 740	35 538	268 278
$W_{\mathrm{GRID,exp}}$	Exported grid electricity	48 400	103 334	15 778	119 112
W_{PV}	On-site PV Electricity	242 447	0	242 447	242 447
$Q_{\mathrm{C,FC}}$	Aero thermal energy, Free cooling	161 220	0	161 220	161 220

$$W_{\mathrm{MTS}} = W_{\mathrm{VCCH}} + W_{\mathrm{AUX}} + W_{\mathrm{AUX,FC}} = 25395 + 12561 + 2303$$
$$= 40259 \text{ kWh}$$
$$W_{\mathrm{AUX}} = 12561 = 5131 + 7430 \text{ kWh (cooling tower +}$$
$$+ \text{ cooling distribution)}$$
$$W_{\mathrm{GRID}} + W_{\mathrm{PV}} = \zeta_{\mathrm{SUB}} + W_{\mathrm{PDTS}} + W_{\mathrm{MISC}} + W_{\mathrm{MTS}}$$
$$= 17520 + 236520 + 8760 + 40259 = 303059 \text{ kWh}$$
$$W_{\mathrm{GRID}} = 60612 \text{ kWh} \quad W_{\mathrm{PV}} = 242447 \text{ kWh}$$
$$W_{\mathrm{GRID,del}} = 109012 \text{ kWh}$$
$$W_{\mathrm{GRID,exp}} = 48400 \text{ kWh}$$

Non-Renewable Primary Energy

$$PE_{\mathrm{DC,nren}} = E_{\mathrm{del,el}} \cdot w_{\mathrm{del,nren,el}} - E_{\mathrm{exp,el}} \cdot w_{\mathrm{del,nren,el}}$$
$$= (109012 - 48400) \cdot 2.135 = 60612 \cdot 2.135 = 129407 \text{ kWh}_{\mathrm{PE,nren}}$$

Total Primary Energy

$$PE_{\mathrm{DC,tot}} = E_{\mathrm{del,el}} \cdot w_{\mathrm{del,tot,el}} - E_{\mathrm{exp,el}} \cdot w_{\mathrm{exp,tot,el}} = 60612 \cdot 2.461$$
$$= 149166 \text{ kWh}_{\mathrm{PE,tot}}$$

CO_2 emissions

$$EM_{\mathrm{DC,CO_2}} = E_{\mathrm{del,el}} \cdot w_{\mathrm{del,CO_2,el}} - E_{\mathrm{exp,el}} \cdot w_{\mathrm{exp,CO_2,el}}$$
$$= 60612 \cdot 0.348 = 21093 \text{ kgCO}_2$$

PUE

$$\mathrm{PUE_3} = \frac{E_{\mathrm{del,el}} \cdot w_{\mathrm{del,tot,el}} - E_{\mathrm{exp,el}} \cdot w_{\mathrm{del,tot,el}} + E_{\mathrm{ren,el}} \cdot w_{\mathrm{del,tot,el}}}{P_{IT} \cdot w_{\mathrm{del,tot,el}}}$$

$$= \frac{(109012 \cdot 2.461) - (48400 \cdot 2.461) + (242447 \cdot 2.461)}{(210240 \cdot 2.461)} = 1.44$$

RER-Renewable Energy Ratio

$$
\begin{aligned}
\mathrm{RER_{EP}} &= \frac{\begin{array}{c} E_{\mathrm{ren,el}} + E_{\mathrm{ren,cool}} + (w_{\mathrm{del,tot,el}} - w_{\mathrm{del,nren,el}}) \cdot E_{\mathrm{del,el}} - \\ - (w_{\mathrm{exp,tot,el}} - w_{\mathrm{exp,nren,el}}) \cdot E_{\mathrm{exp,el}} \end{array}}{E_{\mathrm{ren,el}} + E_{\mathrm{ren,cool}} + (w_{\mathrm{del,tot,el}} \cdot E_{\mathrm{del,el}}) - (w_{\mathrm{exp,tot,el}} \cdot E_{\mathrm{exp,el}})} \\[2mm]
&= \frac{\begin{array}{c} W_{\mathrm{PV}} + Q_{\mathrm{C,FC}} + (w_{\mathrm{del,tot,el}} - w_{\mathrm{del,nren,el}}) \\ \cdot (W_{\mathrm{GRID,del}} - W_{\mathrm{GRID,exp}}) \end{array}}{W_{\mathrm{PV}} + Q_{\mathrm{C,FC}} + w_{\mathrm{del,tot,el}} \cdot W_{\mathrm{GRID,del}} - w_{\mathrm{exp,tot,el}} \cdot W_{\mathrm{GRID,exp}}} \\[2mm]
&= \frac{242477 + 161220 + (2.461 - 2.135) \cdot (109012 - 48400)}{242477 + 161220 + 2.461 \cdot (109012 - 48400)} = 77\%
\end{aligned}
$$

Capacity Metrics

$$\mathrm{CC_{IT,inst}} = 1 - (P_{\mathrm{IT}}/P_{\mathrm{IT,inst}}) = 1 - \left(\frac{24}{28.8}\right) = 17\%$$

$$\mathrm{CC_{IT,des}} = 1 - (P_{\mathrm{IT,inst}}/P_{\mathrm{IT,des}}) = 1 - \left(\frac{28.8}{31.7}\right) = 9\%$$

$$\mathrm{CC_{fac,inst}} = 1 - (P_{\mathrm{fac}}/P_{\mathrm{fac,inst}}) = 1 - \left(\frac{144}{172.8}\right) = 17\%$$

$$\mathrm{CC_{fac,des}} = 1 - (P_{\mathrm{fac,inst}}/P_{\mathrm{fac,des}}) = 1 - \left(\frac{172.8}{172.8}\right) = 0\%$$

$$CC_{\mathrm{IT,m2}} = 1 - \left(\frac{\text{Actual whitespace } m2 \text{ occupied}}{\text{Design withespace } m2}\right) = 1 - \left(\frac{13}{18}\right) = 28\%$$

3.6.2 Example 2. District Cooling and Heat Reuse

Example 2 corresponds to a concept where chilled water for aircooling is supplied by a district cooling system to the Data Centre. Additionally, heat from direct liquid cooling is reused for space heating by means of a heat pump (Figures 3.15 and 3.16).
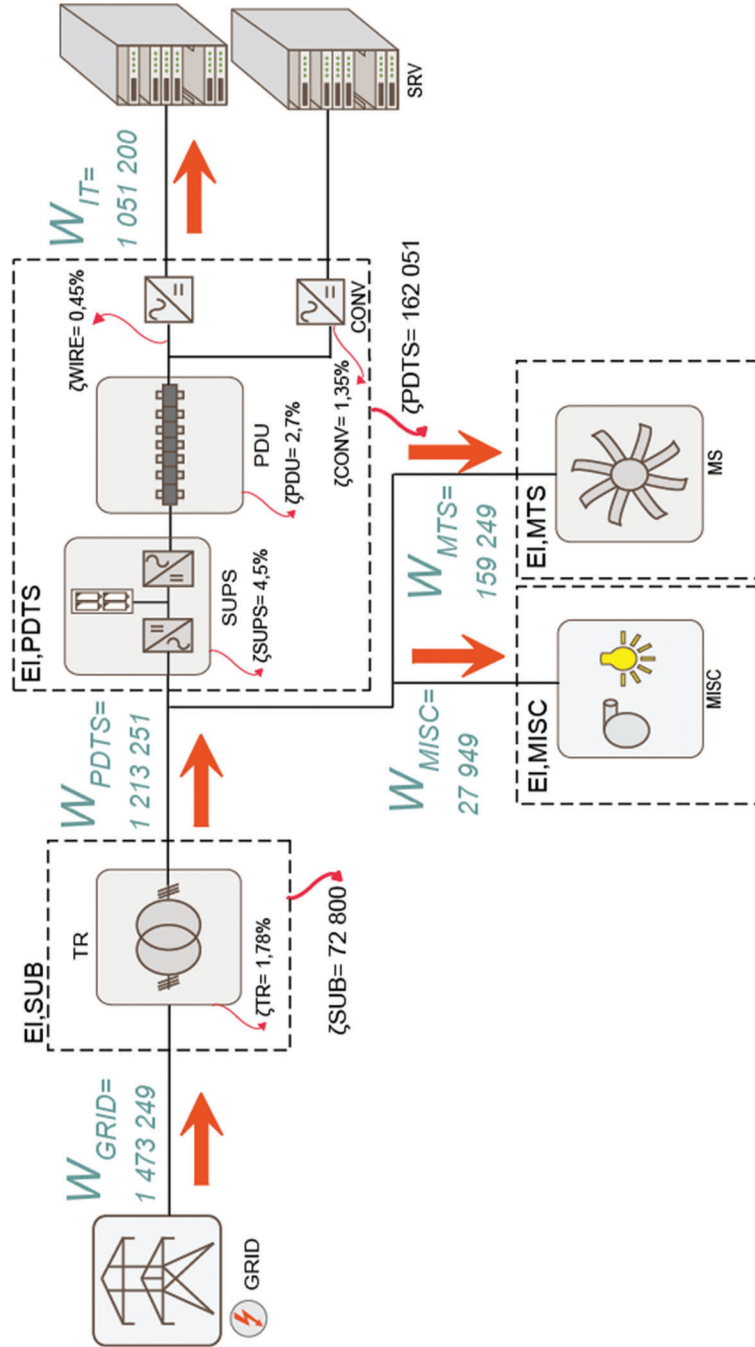
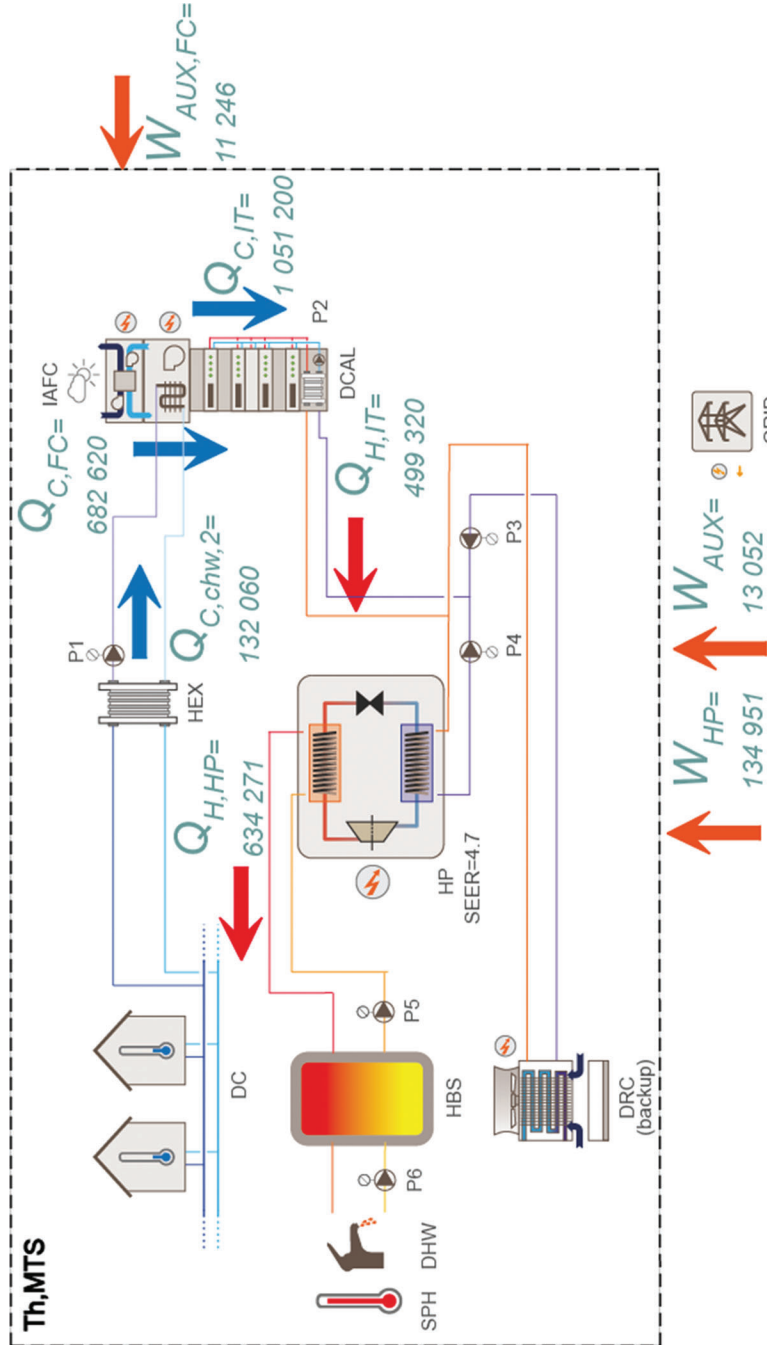**Figure 3.15**   Example 2: District cooling and heat reuse, electrical scheme and main energy flow.

Figure 3.16 Example 2: District cooling and heat reuse, thermal scheme and main thermal and electricity flows linked to the mechanical technical systems.

Main Parameters of the System

The main figures for this example related to the IT power and main losses are similar to the one in Example 3. The location of the case is Chemnitz, and free cooling is used when it is possible. A *COP* of 4.7 is assumed for the heat pump.

Regarding the exported heat, weighting factor different from zero is considered, meaning exported heat will be subtracted in energy balances. It is assumed that the wasted heat is reused in a district heating with non-renewable energy with gas as energy source (Figure 3.17 and Table 3.4).

$$P_{IT} = 120 \text{ kW} \quad P_{fac} = 286.6 \text{ kW}$$

$$P_{IT,inst} = 1.2 \cdot P_{IT} = 144 \text{ kW}_{el}$$

$$P_{fac,inst} = 1.2 \cdot P_{fac} = 343.9 \text{ kW}_{el}$$

$$P_{IT,des} = 1.1 \cdot P_{IT,inst} = 158.4 \text{ kW}_{el}$$

$$P_{fac,des} = 1.0 \cdot P_{fac,inst} = 378.3 \text{ kW}_{el}$$

$$COP_{HP} = 4.7 \quad EER_{FC} = 60.7$$

$$W_{IT} = 1051200 \text{ kWh}$$

$$Q_{C,FC} = 682620 \text{ kWh}_{th}$$

$$Q_{C,chw,2} = 132060 \text{ kWh}_{th}$$

$$Q_{H,HP} = 634271 \text{ kWh}_{th}$$

$$Q_{C,chw,1} = Q_{H,IT} = (Q_{C,IT} - Q_{C,FC} - Q_{C,chw,2}) + \xi_{th,MTS}$$
$$= (1051200 - 682620 - 132060) + 262800 = 499320 \text{ kWh}_{th}$$

$$W_{HP} = \frac{Q_{H,HP}}{\text{SEER}} = \frac{634271}{4.7} = 134951 \text{ kWh}_{el}$$

$$W_{MTS} = W_{HP} + W_{AUX} + W_{AUX,FC} = 134951 + 13052 + 11246$$
$$= 159249 \text{ kW}_{el}$$

$$W_{AUX} = 13052 = 10183 + 2013 + 857 \text{ kWh (cooling tower +}$$
$$+ \text{ cooling distribution } + \text{ heat distribution)}$$

$$W_{GRID} = \zeta_{SUB} + W_{PDTS} + W_{MISC} + W_{MTS}$$
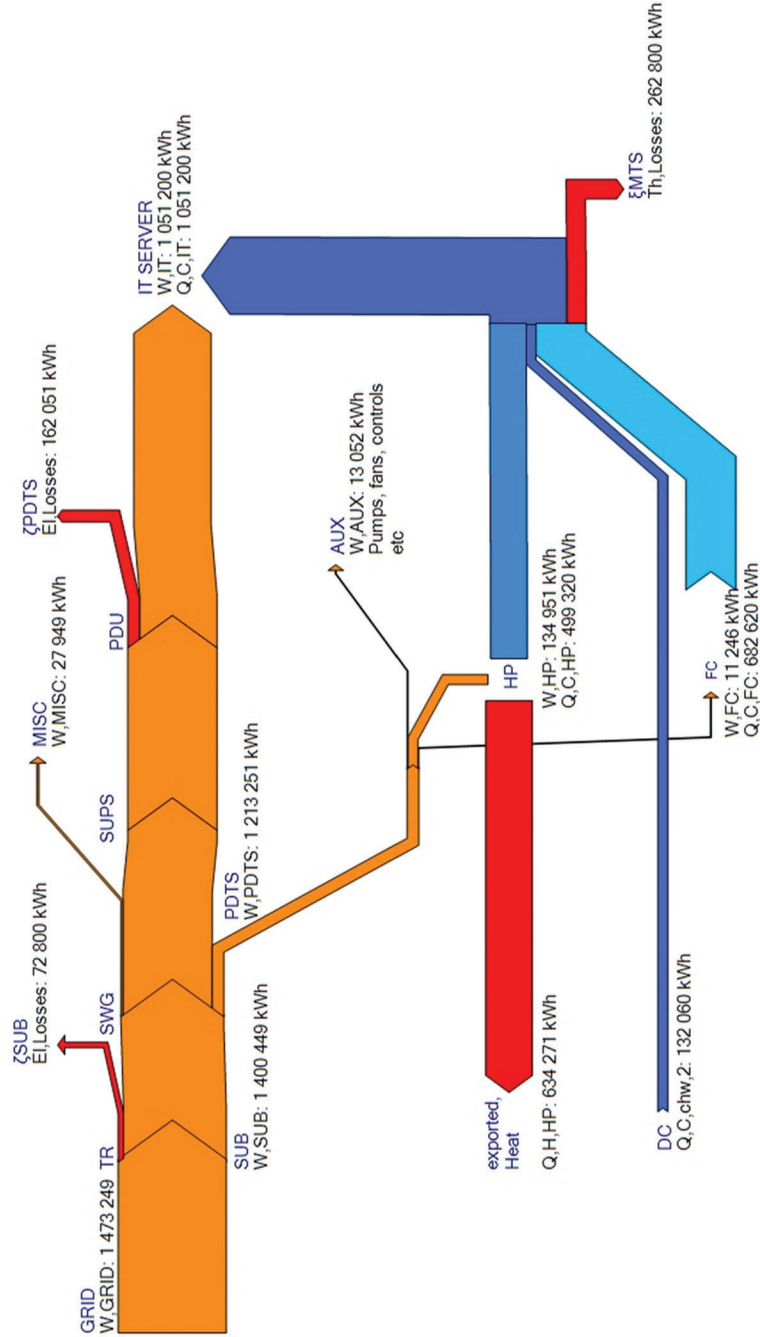$$= 72800 + 1213251 + 27949 + 159249 = 1473249 \text{ kWh}$$

Figure 3.17   Example 1: District cooling and heat reuse, Sankey diagram.

Table 3.4 Example 3. Summary table of main energy flows

Symbol	Definition	kWh/year	PE nren	PE ren	PE tot
$E_{\text{del,el}}$	Delivered grid electricity	1 473 249	3 145 387	480 279	3 625 666
$E_{\text{ren,cool}}$	Aero thermal energy, Free cooling	682 620	0	682 620	682 620
$E_{\text{del,Dcool}}$	District cooling	132 060	26 412	105 648	132 060
$E_{\text{exp,heat}}$	Exported	634 271	634 271	0	634 271

Non-Renewable Primary Energy

$$PE_{\text{DC,nren}} = E_{\text{del,el}} \cdot w_{\text{del,nren,el}} + E_{\text{del,Dcool}} \cdot w_{\text{del,nren,DCool}} -$$

$$- E_{\text{exp,heat}} \cdot w_{\text{exp,nren,heat}} = [(1473249) \cdot 2.135 + 132060 \cdot 0.2] -$$

$$- 634271 \cdot 1.0 = 2537528 \text{ kWh}$$

Total Renewable Primary Energy

$$PE_{\text{DC,tot\_op2}} = E_{\text{del,el}} \cdot w_{\text{del,tot,el}} + E_{\text{del,Dcool}} \cdot w_{\text{del,tot,DCool}} -$$

$$- E_{\text{exp,heat}} \cdot w_{\text{exp,tot,DHeat}} = [(1473249) \cdot 2.461 + 132060 \cdot 1.0]$$

$$- 634271 \cdot 1.0 = 3806075 \text{ kWh}$$

PUE

$$PUE_3 = \frac{E_{del,el} \cdot w_{del,tot,el} + E_{del,Dcool} \cdot w_{del,tot,DCool}}{W_{IT} \cdot w_{del,tot,el}}$$

$$= \frac{1473249 \cdot 2.461 + 132060 \cdot 1.0}{1015200 \cdot 2.461} = \frac{3757726}{2587003} = 1.45$$

Renewable Energy Ratio (RER)

$$\text{RER}_{\text{EP}} = \frac{\begin{array}{c} E_{\text{ren,cool}} + (w_{\text{del,tot,el}} - w_{\text{del,nren,el}}) \cdot E_{\text{del,el}} + \\ + (w_{\text{del,tot,Dcool}} - w_{\text{del,nren,DCool}}) \cdot E_{\text{del,DCool}} \end{array}}{\begin{array}{c} E_{\text{ren,cool}} + (w_{\text{del,tot,el}} \cdot E_{\text{del,el}}) + (w_{\text{del,tot,DCool}} \cdot E_{\text{del,DCool}}) - \\ - E_{\text{exp,heat}} \cdot w_{\text{exp,tot,heat}} \end{array}}$$

$$- \frac{(w_{\text{exp,tot,heat}} - w_{\text{exp,nren,heat}}) \cdot E_{\text{exp,heat}}}{\begin{array}{c} E_{\text{ren,cool}} + (w_{\text{del,tot,el}} \cdot E_{\text{del,el}}) + (w_{\text{del,tot,DCool}} \cdot E_{\text{del,DCool}}) \\ - E_{\text{exp,heat}} \cdot w_{\text{exp,tot,heat}} \end{array}}$$

$$= \frac{\begin{matrix}686620 + (2.461 - 2.135) \cdot 1473249 + (1.0 - 0.2) \cdot 132060 - \\ - (1.0 - 1.0) \cdot 634271\end{matrix}}{686620 + 2.461 \cdot 1473249 + 1.0 \cdot 132060 + 1.0 \cdot 634271}$$

$$= \frac{1268547}{3806075} = 33\%$$

Capacity Metrics

$$\mathrm{CC_{IT,inst}} = 1 - (P_{\mathrm{IT}}/P_{\mathrm{IT,inst}}) = 1 - \left(\frac{120}{144}\right) = 17\%$$

$$\mathrm{CC_{IT,des}} = 1 - (P_{\mathrm{IT,inst}}/P_{\mathrm{IT,des}}) = 1 - \left(\frac{144}{158.4}\right) = 9\%$$

$$\mathrm{CC_{fac,inst}} = 1 - (P_{\mathrm{fac}}/P_{\mathrm{fac,inst}}) = 1 - \left(\frac{286.6}{343.9}\right) = 17\%$$

$$\mathrm{CC_{fac,des}} = 1 - (P_{\mathrm{fac,inst}}/P_{\mathrm{fac,des}}) = 1 - \left(\frac{343.9}{378.3}\right) = 9\%$$

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