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Enhancing energy efficiency in data centers: streamSAVE+ methodologies for energy savings assessment

COLLECTION: MONITORING AND EVALUATION

PEER-REVIEWED PAPER

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ABSTRACT

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The rapid growth of digital services has significantly increased energy consumption in data centers, making their energy performance a key concern within EU energy efficiency and decarbonization strategies. At the same time, the revised Energy Efficiency Directive (EED) introduces strengthened requirements for the monitoring, evaluation, and reporting of energy savings, highlighting the need for robust and harmonized methodologies that can support EU Member States in assessing and reporting the impact of energy efficiency measures. However, existing approaches for calculating energy savings in data centers remain fragmented and often difficult to apply consistently across countries.

This paper presents two streamlined bottom-up methodologies for assessing energy savings in data centers, focusing on improvements in IT equipment and data center infrastructure, with particular emphasis on cooling systems. Developed within the streamSAVE+ project, the methodologies aim to provide simplified yet robust approaches that support consistent energy savings estimation and facilitate reporting under the EED framework. An overview of existing methodologies across EU Member States reveals key gaps, including inconsistent baseline definitions, limited availability of indicative parameter values, and challenges in addressing interactions between IT and cooling systems.

In response, the proposed methodologies define clear system boundaries, baseline approaches, and calculation frameworks for estimating final energy savings. They also introduce indicative parameter ranges and reference assumptions that enable practical application across different national contexts while maintaining methodological consistency. By supporting transparent and comparable energy savings assessments, the methodologies can contribute to improved monitoring and reporting practices and assist policymakers in evaluating energy efficiency improvements in data centers.

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1. INTRODUCTION

The rapid expansion of digital services, cloud computing, and artificial intelligence has led to a substantial increase in the number and capacity of data centers worldwide. As a result, data centers have become an increasingly important source of electricity demand, with significant implications for energy systems, greenhouse gas (GHG) emissions, and energy efficiency policy (IEA 2023; Masanet et al. 2020). Improving the energy performance of data centers is therefore recognized as a key priority within European and international energy and climate strategies, particularly in the context of energy efficiency and long-term decarbonization (European Commission 2023; Bertoldi, Avgerinou and Castellazzi 2017).

Figure 1 illustrates the global distribution of major data center clusters, with circle size representing their respective Information Technology (IT) electricity load in gigawatts (GW) as reported by IEA (IEA 2025).

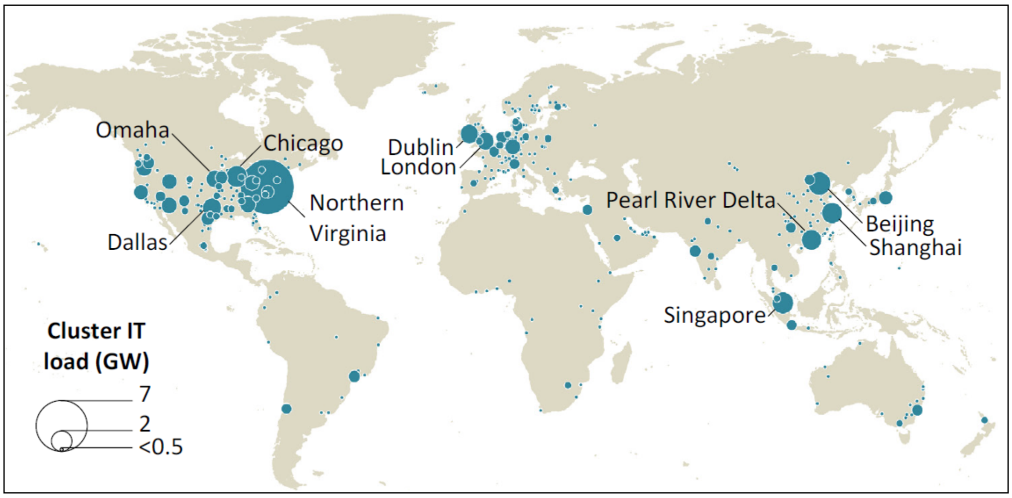

Figure 1 Global map of large data center clusters, 2024.

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This increasing electricity demand also reinforces the relevance of data centers within EU energy policy. Within the EU, the revised Energy Efficiency Directive (EED) (Directive (EU) 2023/1791) strengthens requirements for the monitoring, evaluation, and reporting of energy savings across EU Member States. To support these requirements, Member States need reliable and transparent methodologies capable of estimating energy savings from different sectors and technologies. Bottom-up approaches, including deemed savings and engineering-based calculations, play a central role in this context (European Commission 2019; Rosenow, Cowart and Bayer 2019).

Despite the growing importance of data centers, methodologies for assessing energy savings in this sector remain limited and fragmented. Existing approaches are often developed for specific national contexts and rely on different assumptions, system boundaries, and input parameters, reducing the comparability and transferability of reported savings across EU Member States. Data centers also present specific methodological challenges due to the interactions between IT equipment and supporting infrastructure, particularly cooling systems, as well as variations in workload and operating conditions (Masanet et al. 2020; Hintemann and Hinterholzer 2022).

Recent European initiatives have emphasized the need for harmonized bottom-up methodologies and reliable indicative parameter values to support EED reporting (Renders et al. 2023). In response, the streamSAVE+ project aims to streamline energy savings calculations across multiple priority actions by developing simplified yet robust methodologies applicable across different national contexts (Moorkens et al. 2025a; Moura et al. 2025).

Within the project, five priority actions were identified through stakeholder consultation, including IT equipment and cooling systems in data centers (Melmuka and Brandl 2026). Data centers were considered a particularly relevant and challenging sector due to their rapidly increasing electricity demand and the strong interaction between IT and cooling systems.

In this context, this paper presents two streamlined bottom-up methodologies for assessing energy savings in data centers, focusing on improvements in IT equipment and cooling systems. The methodologies aim to support transparent and consistent estimation of energy savings for policy evaluation and reporting under the EED framework. The paper also reviews existing methodologies across EU Member States and discusses how the proposed approaches can improve the consistency and comparability of reported savings.

The remainder of the paper is structured as follows. Section 2 presents the policy and methodological context and reviews existing bottom-up methodologies for data centers. Sections 3 and 4 present the methodologies for IT equipment and cooling systems, respectively. Section 5 discusses the findings and their relevance for policy evaluation and reporting, and Section 6 concludes the paper.

2. POLICY AND METHODOLOGICAL CONTEXT

2.1. POLICY AND METHODOLOGICAL CONTEXT FOR ENERGY SAVINGS ASSESSMENT

The revised EED establishes a comprehensive framework for reducing energy consumption across all sectors and reinforces requirements for the monitoring, evaluation, and reporting of achieved savings, particularly under Article 8 on energy savings obligations and related provisions (European Commission 2023). These requirements increase the need for robust and transparent methodologies capable of calculating and reporting energy savings in a consistent and comparable manner across EU Member States (Rosenow 2023; Rosenow, Cowart and Bayer 2019).

Bottom-up approaches, including deemed savings, metered savings, and engineering-based calculations, play a central role in supporting national reporting and evaluation under the EED framework. These approaches quantify energy savings from specific actions using standardized parameters, default values, and engineering assumptions and are widely applied in energy efficiency obligation schemes and alternative policy measures (European Commission 2019; Labanca and Bertoldi 2016). However, differences in national practices, data availability, and methodological assumptions continue to generate heterogeneous approaches across EU Member States, reducing the comparability and transparency of reported savings and complicating cross-country benchmarking and policy evaluation. This highlights the need for harmonized yet flexible methodologies that can be applied across different national contexts (Renders et al. 2023; ENSMOV Plus 2024).

To address these challenges, the streamSAVE+ project was launched to support Member States in streamlining energy savings calculations and improving the consistency of bottom-up methodologies used for policy design, implementation, and reporting under the EED. Building on previous work developed within the H2020 streamSAVE project, streamSAVE+ aims to improve the comparability and transparency of reported savings across countries and strengthen the capacity of national authorities to monitor and evaluate energy efficiency improvements. It also supports knowledge exchange among EU Member States and the development of practical tools and guidance for the application of bottom-up methodologies. This paper presents two of the five newly developed calculation methodologies.

Within the streamSAVE+ project, five priority actions were identified through stakeholder consultation based on their relevance for energy savings and methodological development (Melmuka et al. 2026). These include deep renovations in buildings, IT equipment and cooling systems in data centers, heat recovery in ventilation systems, and public traffic management. The developed methodologies aim to provide simplified yet robust approaches that support both ex-ante estimation and ex-post reporting of energy savings through transparent calculation frameworks, clear system boundaries, and indicative parameter values derived from European data sources and expert knowledge (Moorkens et al. 2025a).

Among the identified priority actions, data centers represent a particularly relevant and challenging sector for energy savings assessment due to their rapidly growing electricity consumption and the strong interaction between IT equipment and supporting infrastructure, especially cooling systems. Recent estimates indicate that global data center electricity consumption could more than double to around 945 TWh by 2030 (IEA 2025). Variations in workload, operating conditions, and cooling requirements complicate the definition of baselines and performance indicators and limit the transferability of existing national

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methodologies. In addition, the limited availability of transparent site-specific energy consumption data and the rapid evolution of data center technologies and operational practices further increase the need for robust and adaptable methodologies (Masanet et al. 2020; Hintemann and Hinterholzer 2022).

In this context, the development of streamlined methodologies specifically tailored to data centers aims to address existing methodological gaps and support more consistent and transparent assessment of energy efficiency improvements in this rapidly growing sector.

2.2. EXISTING BOTTOM-UP METHODOLOGIES FOR DATA CENTERS

A comprehensive mapping of bottom-up energy savings methodologies across EU Member States was conducted within the streamSAVE+ project and is documented in Moura et al. (2025). Based on national methodology catalogues and related project outputs, the mapping identified 773 bottom-up energy savings calculation methodologies across 24 catalogues covering 22 countries and two European projects (Moura et al. 2025).

Despite this extensive methodological landscape, only five methodologies were identified as directly applicable to data center-related measures, including one methodology for IT equipment and four methodologies for cooling systems across different EU Member States. This highlights the very limited methodological coverage of this rapidly growing sector.

As summarized in Table 1, the identified methodologies focus mainly on specific technological upgrades. These methodologies generally rely on engineering-based calculations comparing baseline and improved energy consumption under assumed operating conditions (Moura et al. 2025).

Table 1 Overview of existing bottom-up methodologies for data center-related measures (based on Moura et al. 2025).

COUNTRY	SCOPE	TYPE OF MEASURE	APPROACH	KEY CHARACTERISTICS
Czech Republic	IT equipment	Legislative methodology	Engineering-based	Based on national regulation and standardized parameters
Czech Republic	Cooling	Legislative methodology	Engineering-based	Integrated assessment of data center cooling performance
France	Cooling	Containment systems	Deemed/ engineering	Focus on hot/cold aisle containment
France	Cooling	Free cooling systems	Engineering-based	Replacement of chillers with free cooling
Luxembourg	Cooling	Efficiency improvement	Engineering-based	General improvement of data center infrastructure

The review of existing methodologies reveals substantial differences in system boundaries, baseline definitions, and calculation parameters. In many cases, baseline energy consumption is estimated using simplified assumptions regarding equipment performance or average operating conditions, without a consistent normalization framework across different data center types and operational contexts. The use of performance indicators and input parameters also varies considerably across methodologies, reflecting differences in national practices and data availability.

Another important limitation concerns the availability and harmonization of indicative parameter values and supporting assumptions. Existing methodologies often rely on country-specific data or project-based assumptions for parameters such as equipment lifetime, utilization rates, load factors, operating hours, and typical efficiency improvements. These assumptions are rarely documented in a standardized manner, limiting transparency, comparability, and transferability across Member States.

Overall, the mapping demonstrates that methodological coverage for data center energy efficiency measures remains limited and fragmented. The limited number of available methodologies, combined with inconsistencies in system boundaries, baseline definitions, and parameter values, complicates the comparison and aggregation of reported savings under the EED framework. These gaps highlight the need for streamlined and harmonized methodologies specifically tailored to data centers, which constitutes the main motivation for the methodologies presented in the following sections.

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3. STREAMLINED BOTTOM-UP METHODOLOGY FOR IT EQUIPMENT IN DATA CENTERS

This section presents the streamlined bottom-up methodology developed within the streamSAVE+ project to estimate energy savings from improvements in IT equipment in data centers. The methodology aims to provide a transparent and consistent framework for energy savings estimation and reporting under the EED, while remaining flexible enough to accommodate country-specific data and assumptions. The following subsections describe the system boundaries, baseline definition, calculation framework, and indicative parameters proposed for its implementation.

3.1. SCOPE AND SYSTEM BOUNDARIES

The methodology covers the main categories of IT equipment typically deployed in data centers, namely servers, storage systems, and networking equipment. It also includes operational measures affecting their energy consumption, such as equipment replacement, virtualization and workload consolidation, and other actions leading to measurable reductions in electricity use. Figure 2 illustrates the system boundaries of the methodology, highlighting the separation between IT loads and supporting infrastructure.

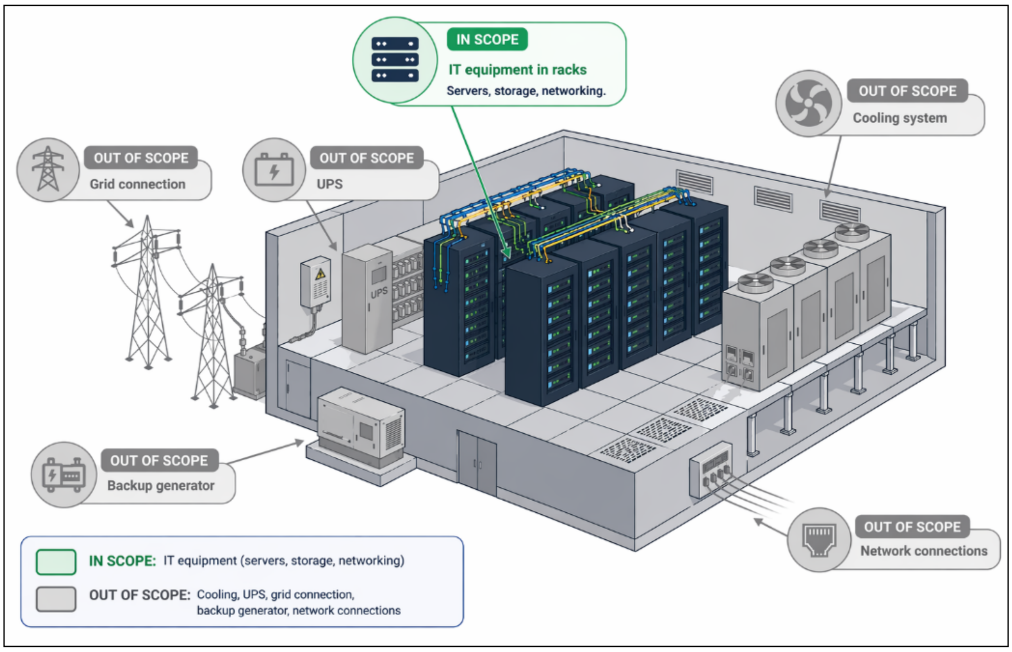

Figure 2 System boundaries for the IT equipment methodology. IT equipment is in scope, while cooling and supporting infrastructure are excluded.

System boundaries are defined at the level of IT equipment and associated electricity consumption. Energy savings are calculated based on changes in final electricity consumption attributable to the implemented measures. The methodology assumes comparable service levels between the baseline and reporting situations, ensuring that calculated savings reflect efficiency improvements rather than changes in activity or service provision.

The methodology can be applied using measured data or indicative parameter values, depending on data availability. While focused on direct IT electricity consumption, the approach remains compatible with complementary methodologies addressing other data center subsystems, such as cooling, allowing transparent attribution of savings and consistent integration into national reporting frameworks.

3.2. CALCULATION FRAMEWORK

The methodology enables the calculation of final energy savings for reporting under Article 8 of the EED, the assessment of impacts on energy consumption under Article 4, and the estimation of associated greenhouse gas emissions reductions using a consistent set of parameters and assumptions (Moorkens et al. 2025a).

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Energy savings are estimated by comparing the energy consumption of IT equipment within the defined system boundaries (Figure 2) before and after the implementation of energy efficiency measures under comparable operating conditions. Final energy savings for reporting under Article 8 of the EED are calculated using Equation (1), where $TFES_{IT}$ represents total final energy savings of IT equipment (in kWh/a), EC_{bef} represents total annual electricity consumption before implementation of the measure (in kWh/a), PUE represents power usage effectiveness (dmnl), $S_{IT,comp}$ represents the proportion of IT electricity consumption attributed to the considered load component (e.g., servers, storage systems, or networking equipment) (in %), and ES_m represents the relative energy savings associated with the implemented measure (in %).

$$TFES_{IT} = \frac{EC_{bef}}{PUE} \cdot S_{IT,comp} \cdot ES_m \tag{1}$$

This formulation links the electricity consumption of the affected IT equipment with data center performance parameters and measure-specific savings factors. PUE is defined as the ratio between total data center energy consumption and the energy consumed by IT equipment and is calculated in accordance with ISO/IEC 30134-2:2018 and EN 50600-4-2 (ISO/IEC 2018; CENELEC 2016). While other indicators exist, such as the Energy Reuse Factor (ERF), PUE remains the most widely used metric for assessing infrastructure efficiency and is therefore adopted in this methodology.

The impact of implemented measures on energy consumption is calculated using Equation (2), where $EPEC_{IT}$ represents the change in primary energy consumption of IT equipment, $TFES_{IT}$ represents total final energy savings of IT equipment, and $f_{PE,electricity}$ represents the primary energy conversion factor for electricity.

$$EPEC_{IT} = TFES_{IT} \cdot f_{PE,electricity} \tag{2}$$

The conversion factor from final to primary energy should be based on EU27 average values or national values consistent with Article 4 reporting requirements. Additional indicators, such as the Green Energy Coefficient (GEC), may be used to account for the share of renewable electricity, but are not explicitly included in the present methodology.

Greenhouse gas emissions reductions are calculated using Equation (3), where $GHGSAV_{IT}$ (in tCO_{2eq}/a) represents greenhouse gas emissions savings from IT equipment, $TFES_{IT}$ represents total final energy savings from IT equipment, and $f_{GHG,electricity}$ (in gCO_2/kWh) represents the greenhouse gas emissions factor for electricity.

$$GHGSAV_{IT} = TFES_{IT} \cdot f_{GHG,electricity} \cdot 10^{-6} \tag{3}$$

Emission factors for electricity should be derived from Annex VI of Regulation (EU) 2018/2066 or corresponding national UNFCCC reporting data. Country-specific emission factors should be applied where available, while indicative European values may be used as reference values.

3.2.1. Methodological aspects

The methodology allows the use of measured data or indicative parameter values depending on data availability and the characteristics of the intervention. Parameters such as PUE and the proportion of IT electricity consumption attributed to specific load components are incorporated to ensure that calculated savings reflect efficiency improvements rather than changes in activity levels.

When multiple efficiency measures are applied to the same IT component, the total percentage of energy savings should be calculated sequentially rather than by simple addition. If two independent measures provide relative savings ES_1 and ES_2 (in %), the combined savings ES_{com} are calculated using Equation (4).

$$ES_{com} = 1 - (1 - ES_1)(1 - ES_2) \tag{4}$$

This approach avoids overestimation of combined impacts and prevents double counting. When efficiency measures are applied to different IT components, such as servers, storage, or networking equipment, savings should first be calculated separately for each component and then aggregated to obtain total data center energy savings.

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3.3. INDICATIVE VALUES

The application of the proposed methodology is supported by the indicative parameters and reference values presented in Tables 2–4, which provide representative ranges for key input parameters required for estimating energy savings associated with improvements in IT equipment in data centers.

Table 2 Energy consumption before the implementation of the action and PUE for different categories of data centers.

CATEGORY	IT POWER	EC_{before} [MWh/a]	PUE
Very Small	100–500 kW	650–4,000	1.5–1.8
Small	500–1,000 kW	3,250–8,000	1.4–1.7
Medium	1–2 MW	6,500–17,000	1.3–1.6
Large	2–10 MW	14,000–85,000	1.3–1.5
Very Large	>10 MW	>85,000	1.1–1.4

Table 3 Proportion of IT electricity consumption attributed to each load component.

LOAD	%
Servers	60–70%
Storage Devices	10–15%
Networking	10–15%
Other IT Loads	5–10%

Table 4 Energy savings by type of efficiency measure and lifetime of savings.

LOAD	MEASURE	%	LIFETIME
Servers	Server virtualization and consolidation	20–40%	6 years
Servers	Decommissioning obsolete servers	5–15%	3 years
Servers	Deployment of energy-efficient server hardware	10–25%	5 years
Servers	Intelligent workload scheduling	10–30%	4 years
Servers	Activation of power management features	5–20%	4 years
Servers	Efficient virtualization/container platforms	10–20%	5 years
Servers	Monitoring and analytics for server energy use	0–5%	2 years
Storage	Data management optimization	5–15%	4 years
Storage	Storage tiering and energy-aware systems	10–20%	5 years
Storage	Modernization of storage hardware	10–20%	5 years
Network	Efficient network design and topology optimization	5–15%	4 years
Network	Energy-efficient network equipment	5–15%	5 years
Network	Intelligent port and link management	5–10%	4 years
Network	Monitoring network device consumption	0–5%	2 years

Figure 3 illustrates how larger data centers are typically associated with higher IT power capacity and annual electricity consumption while achieving improved infrastructure efficiency, reflected by lower PUE values. The figure is derived from the indicative ranges presented in Table 2 and illustrates the relationship between facility scale, electricity consumption, and infrastructure efficiency. The figure highlights three main trends: increasing electricity consumption with facility size, improved infrastructure efficiency in larger facilities, and reduced PUE values associated with economies of scale and more advanced cooling and infrastructure management systems.

Due to the diversity of data center designs, operating models, and technological configurations, the methodology adopts representative parameter ranges rather than rigid default values. Implementers are expected to use measured or calculated values whenever possible, supported by indicative ranges derived from European and international data sources.

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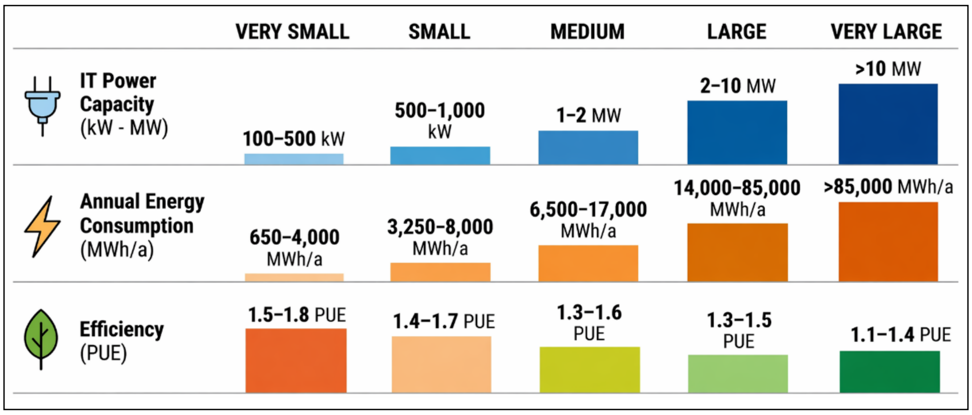

Figure 3 Data center scaling – power capacity and efficiency.

The indicative values presented in Tables 2–4 are derived from a synthesis of multiple data sources, sectoral benchmarks, and project-level analyses rather than from a single study. The reported ranges reflect typical operating conditions and performance parameters across different data center types and national contexts. Further details on the data sources, assumptions, and derivation process are provided in Moorkens et al. (2025a).

Key inputs such as IT electricity consumption, PUE, and IT load distribution are based on recent European and international studies and sectoral benchmarks (Booth et al. 2024; European Commission 2024; International Energy Agency 2023; United States Department of Energy 2024; Uptime Institute 2024).

Although the methodology includes indicative ranges to support calculations, actual energy savings should be estimated using measured or documented data before and after implementation wherever feasible. Site-specific data improve the accuracy and representativeness of savings estimates.

The methodology is also designed to evolve with improved data availability. Under the revised EED, data centers with an installed IT power of 500 kW or more are required to report annually on their energy performance, including metrics such as total and IT-specific energy consumption, PUE, cooling efficiency, renewable energy share, and waste heat reuse (European Commission 2023). Although initial datasets are already becoming available, they are not yet sufficiently complete or harmonized to support a systematic refinement of the indicative values presented in this study. Over time, these datasets are expected to support the development of more granular and nationally specific benchmarks.

3.3.1. Illustrative example

To illustrate the application of the methodology, consider a medium-size data center with an annual electricity consumption before the implementation of the measure of 10 GWh/a and a PUE of 1.4, consistent with the indicative ranges presented in Table 2.

Assume the implementation of a server virtualization and consolidation measure with a relative energy savings of 30%, within the indicative range of 20–40% presented in Table 4. Servers are assumed to represent 65% of total IT load, based on the indicative range of 60–70% presented in Table 3.

Final energy savings are calculated using Equation (1):

$$TFES_{IT} = \frac{EC_{bef}}{PUE} \cdot S_{IT,comp} \cdot ES_m = \frac{10{,}000{,}000}{1.4} \cdot 65\% \cdot 30\% = 1{,}392{,}857\, kWh/a$$

The corresponding impact on primary energy consumption is calculated using Equation (2). Assuming a primary energy conversion factor of 2.1:

$$EPEC_{IT} = TFES_{IT} \cdot f_{PE,electricity} = 1{,}392{,}857 \cdot 2.1 = 2{,}925{,}000\,\text{kWh}/a$$

Greenhouse gas emissions savings are calculated using Equation (3). Assuming an emission factor of 250 gCO_2/kWh:

$$GHGSAV_{IT} = TFES_{IT} \cdot f_{GHG,electricity} \cdot 10^{-6} = 1{,}392{,}857 \cdot 250 \cdot 10^{-6} = 348\text{t}\, CO_{2eq}/\text{a}$$

This example illustrates how measure-specific savings and IT load shares are combined within the proposed calculation framework.

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4. STREAMLINED BOTTOM-UP METHODOLOGY FOR COOLING SYSTEMS IN DATA CENTERS

This section presents the bottom-up methodology developed to estimate energy savings associated with improvements in data center cooling systems. The methodology follows the same general principles and calculation framework described for IT equipment in Section 3. To avoid repetition, only cooling-specific aspects are detailed in this section.

4.1. SCOPE AND SYSTEM BOUNDARIES

The methodology focuses on energy savings resulting from improvements in data center cooling systems. It covers measures affecting the electricity consumption of cooling infrastructure, including upgrades to cooling technologies, airflow management optimization, free cooling solutions, control system improvements, and other actions leading to measurable reductions in cooling-related electricity consumption.

System boundaries are defined at the level of cooling-related electricity consumption associated with maintaining appropriate operating conditions for IT equipment. Energy savings are assessed based on changes in overall data center energy performance resulting from improvements in cooling efficiency under comparable IT service levels and operating conditions. Figure 4 illustrates the system boundaries of the cooling methodology, highlighting the separation between cooling systems and IT loads.

The methodology is applicable to different data center types and cooling configurations and can be implemented using measured data or indicative parameter values depending on data availability. Where possible, measured data before and after implementation should be used to improve the accuracy of the estimated savings. The methodology is not intended for newly constructed data centers unless a clearly defined and validated pre-commissioning baseline PUE is available.

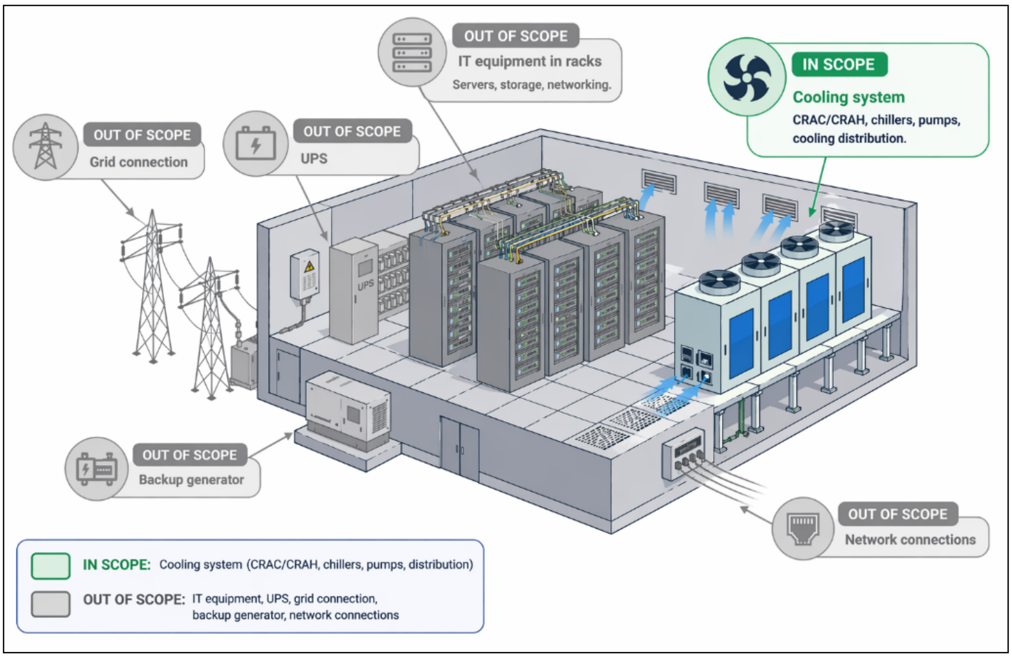

Figure 4 System boundaries for the cooling methodology. Cooling systems are in scope, while IT equipment and other infrastructure are excluded.

4.2. CALCULATION FRAMEWORK

The calculation framework for cooling-related measures follows the general approach described in Section 3.2 and is designed to estimate energy savings attributable to cooling systems.

Final energy savings associated with improvements in cooling systems are calculated using Equation (5), where $TFES_{Cool}$ (in kWh/a) represents total final energy savings attributable to cooling, $EC_{IT,bef}$ (in kWh/a) the annual IT electricity consumption before implementation of the action, $S_{Cool,bef}$ and $S_{Cool,aft}$ (in %) the share of cooling within non-IT loads before and after implementation, respectively, and PUE_{bef} and PUE_{aft} (dmnl) the corresponding PUE values.

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$$TFES_{Cool} = EC_{IT,bef} \cdot \left[(PUE_{bef} - 1) \cdot S_{Cool,bef} - (PUE_{aft} - 1) \cdot S_{Cool,aft} \right] \quad (5)$$

Equation (5) estimates the energy savings attributable specifically to cooling-system improvements. The inclusion of the cooling share parameter enables the allocation of overall infrastructure efficiency improvements to the cooling subsystem, consistent with the defined system boundaries. PUE, defined as the ratio between total data center energy consumption and IT electricity consumption, is used as the main indicator of infrastructure efficiency.

4.2.1. Methodological aspects

The methodology is designed to isolate savings attributable to cooling systems; therefore, parameters such as the cooling share are used to allocate overall infrastructure energy changes to the cooling subsystem. Measured data before and after implementation should be used wherever available. Where measured data is not available, indicative parameter values and representative assumptions may be applied.

Particular attention should be given to the estimation of PUE values before and after implementation. These values should be based on representative operating conditions to ensure that changes in PUE reflect actual efficiency improvements rather than short-term operational variations. The share of cooling within non-IT electricity consumption should also be determined using measured data or representative benchmarks consistent with the characteristics of the data center under consideration.

The methodology assumes comparable IT service levels and operating conditions between the baseline and reporting situations so that calculated savings reflect cooling efficiency improvements rather than changes in workload or service provision. Significant changes in IT workload or infrastructure configuration may require normalization adjustments or complementary methodologies.

Where multiple actions are implemented simultaneously, care should be taken to avoid double counting and to distinguish cooling-related savings from changes in IT electricity consumption.

Different calculation approaches and parameter assumptions may lead to variations in estimated energy savings. For testing and validation purposes, results obtained from the analytical formulas may therefore be compared with those generated by the streamSAVE+ platform implementation, which includes the methodologies implemented in a standardized format with embedded formulas, indicative values, and predefined calculation routines (streamSAVE+ 2025; Moorkens et al. 2025b).

4.3. INDICATIVE VALUES

The application of the proposed cooling methodology is supported by the indicative parameters and reference values presented in Tables 5–7, which provide representative ranges for key input parameters required for estimating energy savings associated with improvements in data center cooling systems.

Table 5 Reference values for PUE for different cooling technologies of data centers.

TECHNOLOGY	PUE_{before}	PUE_{after}	LIFETIME
Upgrade CRAC/CRAH units to variable-speed systems	>1.8	1.5–1.6	15 years
Transition to chilled water system with air-side economizers	>1.6	1.3–1.5	15 years
Implement free cooling (air-side, water-side, TES etc.)	1.6–1.8	1.2–1.4	15 years
Deploy liquid cooling (direct-to-chip or immersion)	1.6–1.8	1.02–1.1	15 years
Optimize two-phase/passive cooling (e.g., thermosiphon loops)	1.5–1.7	1.1–1.3	15 years
Integrate thermal energy storage (TES) for peak shaving and free cooling	1.6–1.8	1.2–1.4	15 years

Figure 5 compares baseline and post-optimization PUE values for different data center cooling technologies. It illustrates the efficiency improvements achievable through liquid cooling, passive systems, free cooling, chilled water systems, thermal energy storage integration, and upgraded computer room air conditioning/computer room air handling (CRAC/CRAH) units. The figure is based on the indicative values presented in Table 5.

CATEGORY	IT POWER	non-IT LOADS [MWh/a]	COOLING [MWh/a]
Very Small	100–500 kW	360–2,700	293–2,000
Small	500–1,000 kW	1,900–5,700	1,300–3,600
Medium	1–2 MW	4,000–13,000	2,275–6,800
Large	2–10 MW	9,300–65,000	4,200–29,750
Very Large	>10 MW	>65,000	>21,250–>25,500

Table 6 Energy consumption of non-IT loads, including cooling, uninterruptible power supply (UPS), and lighting, before the implementation of the action for different categories of data centers.

CATEGORY	IT POWER	$S_{Cooling}$ [%]
Very Small	100–500 kW	75%–80%
Small	500–1,000 kW	65%–70%
Medium	1–2 MW	50%–55%
Large	2–10 MW	44%–48%
Very Large	>10 MW	32%–40%

Table 7 Estimated share of cooling in non-IT load for different categories of data centers.

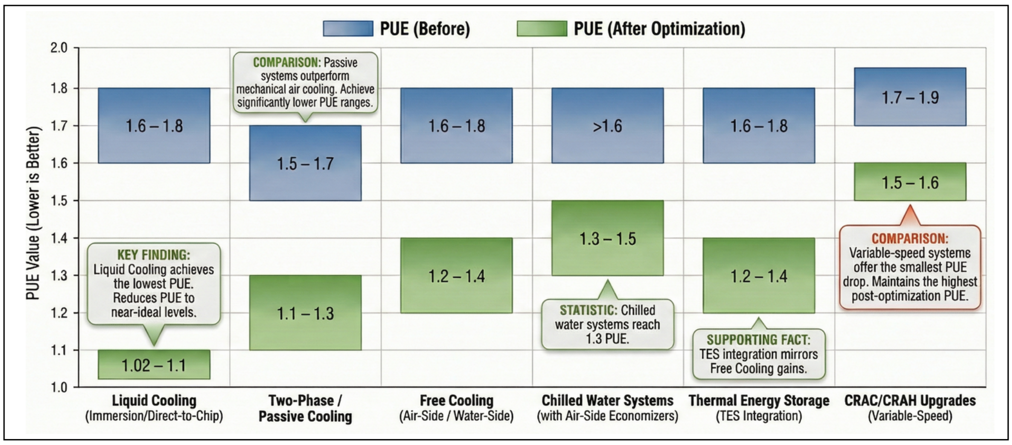

Figure 5 Comparison of baseline and optimized PUE values across data center cooling technologies.

Advanced cooling solutions, particularly liquid cooling and two-phase/passive systems, achieve the largest reductions in PUE, while free cooling, chilled water systems with economizers, thermal energy storage integration, and variable-speed CRAC/CRAH upgrades provide more moderate improvements.

The indicative values presented in Tables 5–7 follow the same derivation approach described for Tables 2–4, being based on a synthesis of multiple data sources, sectoral benchmarks, and project-level analyses rather than on individual studies. Further details on the underlying data sources and assumptions are provided in Moorkens et al. (2025a).

Indicative baseline and improved PUE values are derived from recent technical literature and studies covering different cooling technologies and system configurations, including CRAC/CRAH upgrades, chilled-water systems with economizers, free cooling, liquid cooling, passive or two-phase cooling systems, and thermal energy storage integration (Zhou et al. 2024; Alkrush et al. 2024; Mi et al. 2023).

The methodology also requires assumptions regarding the share of cooling within non-IT electricity consumption. Depending on data center design, climate conditions, and cooling technology, the share of cooling in annual non-IT electricity consumption typically ranges from approximately 32% to 80% (Zhang et al. 2022; Li et al. 2024). The indicative ranges presented in Table 7 provide a representative basis for estimating cooling-related savings where site-specific measurements are not available.

Although the methodology includes indicative ranges to support calculations, actual energy savings should be estimated using measured or documented data before and after implementation wherever feasible. Site-specific data improve the accuracy and representativeness of savings estimates.

4.3.1. Illustrative example

To illustrate the application of the cooling methodology, consider a medium-size data center with an annual IT electricity consumption before implementation of 7.14 GWh/a and a PUE of 1.4, consistent with the indicative ranges presented in Tables 2 and 6. This IT electricity consumption corresponds to the previous illustrative example, where the total annual electricity consumption of the data center was 10 GWh/a.

Assume the implementation of a cooling efficiency improvement measure leading to an improvement in PUE from 1.4 to 1.2. The share of cooling within non-IT electricity consumption is assumed to decrease from 50% before implementation to 45% after implementation, in line with the indicative values and methodological assumptions.

Final energy savings attributable to cooling are calculated using Equation (5):

$$TFES_{Cool} = EC_{IT,bef} \cdot \left[\left(PUE_{bef} - 1 \right) \cdot S_{Cool,bef} - \left(PUE_{aft} - 1 \right) \cdot S_{Cool,aft} \right]$$
$$= 7{,}142{,}857 \cdot \left[(1.4 - 1) \cdot 50\% - (1.2 - 1) \cdot 45\% \right] = 785{,}714 \; kWh / a$$

The corresponding impact on primary energy consumption is calculated using Equation (2), assuming a primary energy conversion factor of 2.1:

$$EPEC_{Cool} = TFES_{Cool} \cdot f_{PE,electricity} = 785{,}714 \cdot 2.1 = 1{,}650{,}000 \, \text{kWh} / a$$

Greenhouse gas emissions savings are calculated using Equation (3), assuming an emission factor of 250 gCO_2/kWh:

$$GHGSAV_{Cool} = TFES_{Cool} \cdot f_{GHG,electricity} \cdot 10^{-6} = 785{,}714 \cdot 250 \cdot 10^{-6} = 196 \, \text{t} \; CO_{2eq} / \text{a}$$

This example demonstrates how cooling-related energy savings are derived by combining changes in overall infrastructure efficiency, represented by PUE, with variations in the share of cooling within non-IT electricity consumption.

5. DISCUSSION

The methodologies presented in this paper address an important methodological gap in the assessment of energy savings in data centers across EU Member States. Despite the rapid growth of data center electricity consumption, only a limited number of bottom-up methodologies currently exist for this sector, and existing approaches often rely on different assumptions, system boundaries, and parameter values, limiting the comparability of reported savings under the EED.

The methodologies developed within the streamSAVE+ project aim to provide a coherent and transferable framework for estimating energy savings from both IT equipment and cooling systems. The use of a common methodological structure facilitates aggregation of results at facility, national, and European levels while reducing the risk of double counting.

A key contribution of the proposed methodologies is their alignment with the revised EED. The use of standardized formulas for calculating final energy savings, primary energy impacts, and greenhouse gas emissions reductions supports consistent reporting under Articles 8 and 4 of the Directive and facilitates the integration of data center efficiency measures into national energy efficiency obligation schemes and alternative policy measures.

The separation between IT equipment and cooling methodologies reflects the technical and operational characteristics of data centers while maintaining an integrated perspective on overall energy performance. Dedicated yet compatible methodologies for these subsystems enable more accurate attribution of energy savings and support aggregation across multiple measures and subsystems. Although the cooling methodology is illustrated for cooling systems, the underlying formulation can also be applied to other infrastructure-related improvements affecting PUE.

The use of indicative parameter values derived from European and international benchmarks supports the practical implementation of the methodologies, particularly where detailed measurement data are not available. Representative ranges for parameters such as PUE, IT load distribution, and cooling shares enable consistent estimation of energy savings while maintaining flexibility to incorporate site-specific data where available. However, the accuracy of savings estimates ultimately depends on the representativeness of these values for specific installations and national contexts.

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The revised EED reporting requirements for large data centers are expected to progressively improve the availability of structured operational data, including total and IT-specific energy consumption, PUE, and related indicators. Over time, these datasets may support the refinement of indicative parameters, the development of nationally specific benchmarks, and more accurate energy savings estimation. The increasing availability of operational data may also support advanced benchmarking and analytical approaches for evaluating data center energy performance.

Beyond EED reporting, the proposed methodologies may also support broader policy design and evaluation by enabling more reliable and comparable estimates of energy savings from data center efficiency measures. As digitalization and artificial intelligence continue to increase data center electricity demand, harmonized methodologies for energy savings assessment will become increasingly important for energy efficiency policy and reporting.

6. CONCLUSIONS

This paper presented streamlined bottom-up methodologies for estimating energy savings associated with improvements in IT equipment and cooling systems in data centers. The proposed approaches address the limited availability and fragmentation of existing methodologies across EU Member States and provide a consistent framework for quantifying energy savings in this rapidly growing sector.

By defining clear system boundaries, standardized calculation formulas, and representative indicative parameters, the methodologies support consistent estimation and reporting of energy savings while allowing adaptation to national contexts and data availability. The use of harmonized calculation principles also facilitates the integration of data center efficiency measures into national reporting frameworks under the Energy Efficiency Directive.

The proposed methodologies provide a practical and transferable approach for assessing energy efficiency improvements in data centers. As data availability improves through emerging reporting requirements and monitoring frameworks, the methodologies can be further refined to support more accurate and evidence-based energy savings assessment.

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **PowerPoint Slides.** PowerPoint Slides relating to this article. URI: https://eceeeproceedings.org/articles/38/files/6a58aca145ff7.pdf

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The authors have no competing interests to declare.

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