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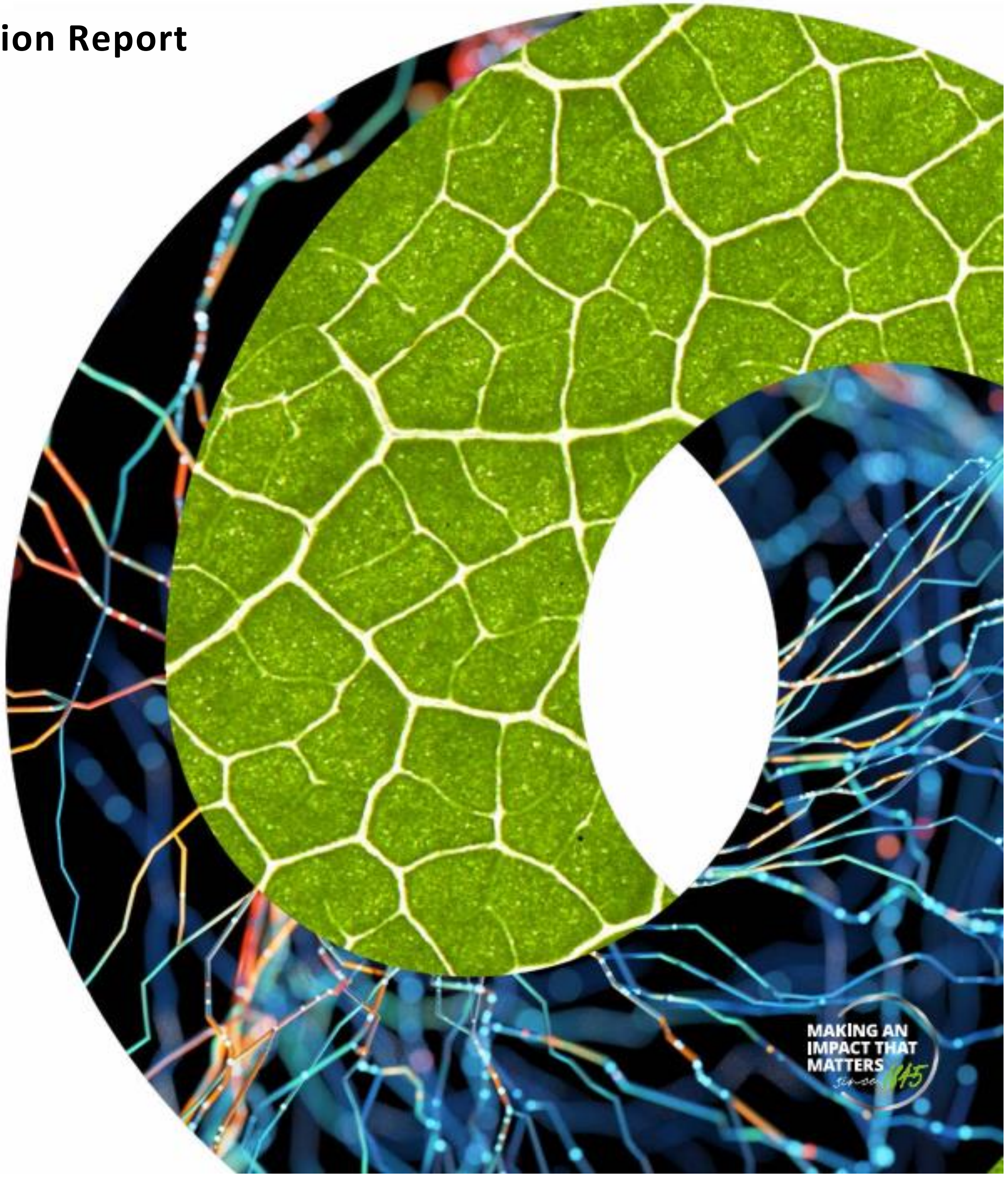
Powering Artificial Intelligence

A study of AI's environmental footprint — today and tomorrow

November 2024

Companion Report



Authors:

Prof. Dr. Bernhard Lorentz
Deloitte Center for Sustainable Progress Founding Chair
Deloitte Germany
+49 1511 4881437
blorentz@deloitte.de

Dr. Johannes Trüby
Deloitte Economics Institute
Deloitte France
+33 1 55 61 62 11
jtruby@deloitte.fr

Geoff Tuff
Sustainability leader for Energy, Resources & Industrials
Deloitte Consulting LLP
+1 617-460-0647
gtuff@deloitte.com

The following specialists crafted and created the insights in this report:

Dr. Quentin Perrier
Deloitte Economics Institute
Senior Manager | Deloitte France

Clémence Lévêque
Deloitte Economics Institute
Consultant | Deloitte France

Bertille Le Dizes
Deloitte Economics Institute
Consultant | Deloitte France

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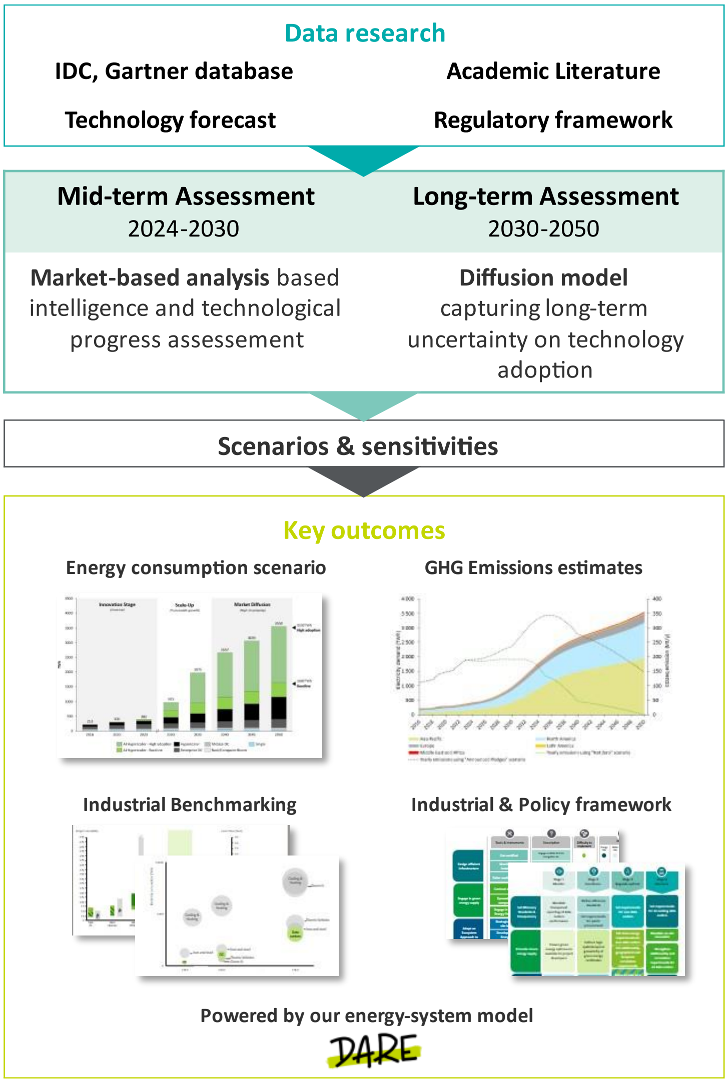
1. Deloitte’s Energy Demand Builder

1.1 Modeling approach for data centers

1. The study “Powering Artificial Intelligence: A study of AI’s environmental footprint — today & tomorrow” is grounded in quantitative, modeling-based analyses conducted by Deloitte.

2. The approach entails bottom-up modeling of the electricity demand and GHG emissions of data centers (DC). In alignment with current best practices [1], it examines key factors such as data center types, locations, equipment, hardware configuration, and technology improvements to project the evolution of electricity consumption. A novel framework within Deloitte’s Energy Demand Builder of the DARE model [2] was developed to carry out the analysis for the Core Report (Figure 1). It is important to note that cryptocurrency mining is excluded from the scope of the study.

Figure 1. Modeling framework.



Source: Deloitte illustration

3. Based on the methodology set out by Shehabi et al. [3], the framework differentiates the electricity consumption of servers, storage, network equipment, and infrastructure. The infrastructure component encompasses data center equipment for both electrical and thermal purposes, such as cooling. This approach allows for the consideration of specific consumption characteristics of each equipment category.

4. Historical data on the number of servers, storage units, network devices are derived from the Gartner database [4] and IDC intelligence [5], the two most referenced data providers for shipment and installed base statistics [6]. These data are segmented by region (Figure 2), based on Garner's scope, and serve as the basis for both historical and medium-term projections of IT stocks (2018-2030).

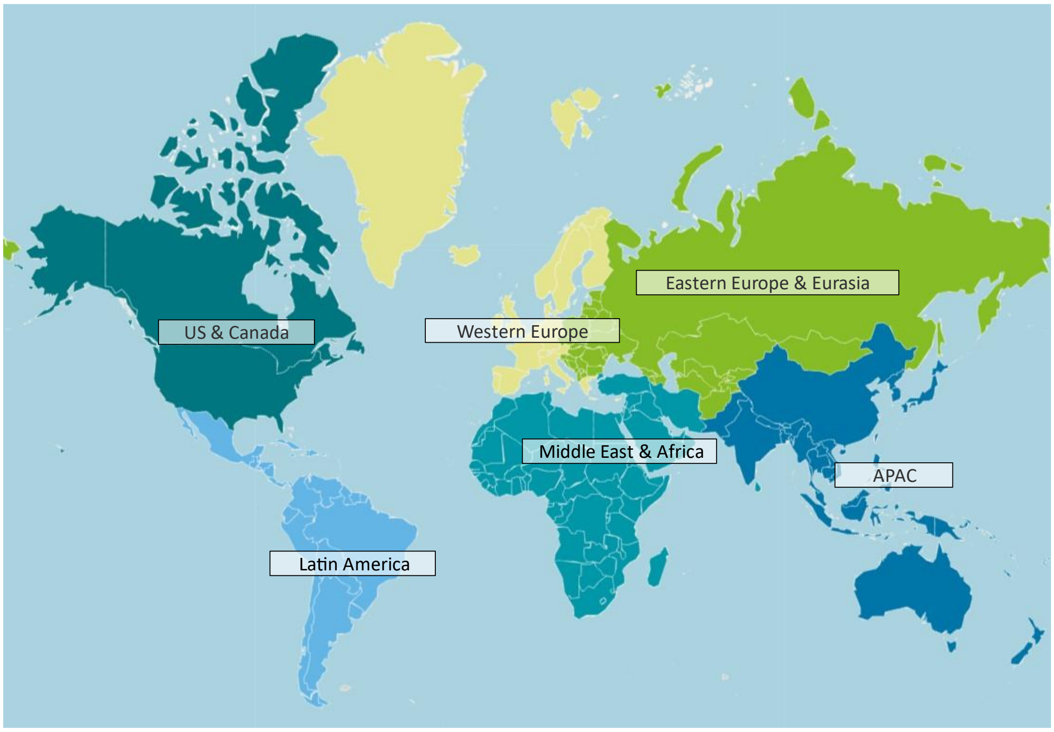
5. Data centers are distributed into six categories (Table 1) and across six regions (Figure 2). We rely on Gartner and IDC near-term analysis to evaluate the evolution of the IT stock in each data center type. Their methodology entails an evaluation of past trends, regional factors, expected shipments, and AI adoption and deployment perspectives. While the Gartner database does not differentiate between data centers used for AI and non-AI purposes, IDC [5] estimates that 10% of global data center electricity demand can be attributed to AI in 2023.

Table 1. Type of data centers considered.

Data centers categories	Number of racks	Square-foot range (m^2)
Single	0	/
Rack/Computer room	1 – 25	0 - 750
Midsize DC	26 – 100	750 – 3,000
Enterprise DC	101 – 500	3,000 – 15,000
Hyperscale DC (non-AI)	500+	> 15,000
AI hyperscale DC	500+	> 15,000

Souce: Deloitte analysis based on Gartner database [4].

Figure 2. Regions considered.



Note: This map does not imply any judgment on the legal status or sovereignty of any territory or on the delimitation of international borders. It is based on Gartner regional grouping [4].

6. Building on the stocks identified per region, electricity consumption is computed by considering data center equipment and operational characteristics. This includes server utilization rates, the evolution of facility energy efficiency, idle power, computing performance, and storage-specific consumption, among others.

Servers

7. To address the uncertainty surrounding the expansion of AI-related workloads, two distinct speeds of AI hyperscale data center development are considered for the study (Table 2). This approach acknowledges the challenges in estimating AI uptake across various sectors and accounts for currently announced investments. The “Baseline” scenario envisions a gradual integration of AI capabilities into existing systems and industries. In this scenario, AI servers are projected to experience a compound annual growth rate (CAGR) of 28% between 2023 and 2028, representing a slowdown compared to the estimated CAGR of 47% observed between 2020 and 2023. This suggests a scenario where AI adoption is limited to the most straightforward and cost-effective applications.

8. Conversely, the “High Adoption” scenario is based on the premise that current AI trends will be sustained, with AI servers following a CAGR of 44% between 2023 and 2028. This growth is driven by an increase in AI workloads and a rapid adoption of generative AI technologies. The projected CAGR is based on an analysis of both demand and supply for AI applications and is supported by near-term projections from the databases used and the literature [5].

9. In both the "Baseline" scenario and the "High Adoption" scenario, projections after 2028 are modeled using sigmoid functions, also referred as S-curve, to model the development and adoption of AI technologies over time [7]. This function accounts for the three phases that new technologies typically undergo [8]. In the first phase, the "early development phase," AI has limited commercial applications, and adoption is slow due to the evolving nature of the technology and its high implementation costs. This phase is followed by the "growth phase" where AI technologies experience rapid growth and widespread adoption across different sectors, facilitated by breakthroughs in the tools developed and its underlying hardware. The final phase is the "maturity phase", during which the growth of AI slows as the technology becomes more established and the market for AI stabilizes.

10. The S-curve is calibrated using historical data and short-term projections of server deployments from 2018 to 2028. This calibration employs non-linear least squares optimization to determine the best-fit parameters for the S-curve function. Applying this optimized function enables the estimation of the number of AI servers from 2028 to 2050. Given that server deployments differ across six global regions, six different S-curves are generated to account for the regional variations in AI adoption rates, technological infrastructure, and current market dynamics.

Table 2. Scenarios description. *

Data center category	Time	Metric	"Baseline" scenario	"High Adoption" scenario
AI hyperscale data centers	*2023-2028*	CAGR of server numbers	28%	44%
	2028-2050	Server numbers	S-curve fit on 2018-2028 data	
		Inflection point	2029	2033
Non-AI hyperscale data centers	*2023-2050*	CAGR trend of server numbers	CAGR decreases by 0.4 p.p per annum	
Other data centers	*2023-2027*	Server numbers	Gartner projections	
	2027-2050	CAGR on server numbers	Based on 2023-2027 CAGR per server type	

(*): Values vary in each region, the data provided reflect the global average across all regions.

11. For non-AI and non-hyperscale data centers, the server installed base is assumed to grow from 2023 – 2027 based on historical rates and databases' forecasts. Beyond 2027, the server installed base continues to grow based on the historical growth rate trend per data center category (Table 2).

12. Based on the installed and projected servers installed base, the associated electricity consumption is computed by:

$$e_{r,i}^{S} = \left(\left(p_{max,i}^{S} - p_{idle,i}^{S}\right) * u_i + p_{idle,i}^{S}\right) * 8760 * N_{r,i}^{S} \qquad \text{(Eq. 1)}$$

Where $e_{r,i}^{S}$ represents the total electricity consumption of server of type i (i.e. midsize server or hyperscale severs, etc.) in the region r, u_i is the utilization rate, $p_{max,i}^{S}$ is the maximum power of the server, $p_{idle,i}^{S}$ is the power consumption at idle state and $N_{r,i}^{S}$ is the number of installed servers of type i in region r. The consumption characteristics depend on the type of data centers where the servers are installed and evolve over time with improvements in efficiency. All relevant data is available in Section **Error! Reference source not found.**.

13. One of the key uncertainties pertains to the evolution of the maximum power over time for a given server type. The approach adopted here has been to consider that the maximum power across data centers increases as the proportion of AI data centers evolves due to the shift from Central Processing Units (CPUs), traditionally used in non-AI data centers, to Graphics Processing Units (GPUs). The CPUs, however, remain at a constant value, in line with the literature [9] and corresponding to a situation where the computing performance (in FLOPS/W) will continue to improve over time.

Storage

14. The current storage installed base, expressed in terabyte capacities, is derived from IDC [10] and Cisco [11]. Future values are projected using the historical CAGR between 2018 and 2023. The total storage base is allocated across regions following the same distribution as the servers installed, reflecting the fact that storage systems will expand where server development occurs.

15. Data storage is divided between hard disk drive (HDD) and solid-state drive (SSD) technologies. The share of SSDs is anticipated to rise slightly, from 11% in 2022 to approximately 15% by 2027 [11]. After 2027, SSDs are expected to stabilize at around 15% of the market. HDDs are expected to remain an important and cost-effective component of data storage, especially in large-scale and cloud data centers. They are projected to continue storing most of the world's data for the foreseeable future [11].

16. The analysis accounts for the different power intensities between HDD and SSD. The associated electricity consumption is calculated using the following formula:

$$e_{r,i}^{ST} = \sum_{HDD/SSD} N_{r,i}^{ST} * p_{HDD/SSD,i}^{ST} * 8760 \qquad \text{(Eq. 2)}$$

where $e_{r,i}^{ST}$ represents the electricity consumption of storage attributed to data center of type i region r, $N_{r,i}^{ST}$ is the installed storage capacity in terabytes, and $p_{HDD/SSD,i}^{ST}$ is the specific power intensity of HDD and SSD technologies.

17. Despite the increasing volume of data being exchanged and utilized, energy efficiency improvements are helping to mitigate and slow the overall increase in consumption. This is notably reflected in the evolution of the power intensity of storage disks, which follows historical trends for future projections [12].

Network equipment

18. Network equipment includes the components used for the transmission of data across the internal data center network. Due to the lack of specific data on port types, it is assumed that 5% of the total electricity consumption of data centers is attributed to network equipment, in line with the existing literature [3]. Given the small share of electricity consumption related to the network equipment, this assumption has only a minimal impact on the modeling results. The electricity consumption is then distributed across all data center types in proportion to the server installed bases.

Infrastructure

19. Infrastructure energy use is calculated using the Power Usage Effectiveness (PUE). It represents the additional electricity consumption linked to the cooling systems and lighting compared to the IT equipment, which includes server, storage, and network-related equipment. A specific PUE value is considered for each data center type and region ($PUE_{r,i}$). It evolves over time based on energy efficiency improvement[1]. The infrastructure energy use ($e^{I}_{r,i}$) is computed using the following equation:

$$e^{I}_{r,i} = \left(e^{S}_{r,i} + e^{ST}_{r,i} + e^{N}_{r,i}\right) * \left(PUE_{r,i} - 1\right)$$

where $e^{N}_{r,i}$ represents the electricity consumption from network equipment.

1.2 Data assumptions

Table 3. Servers' characteristics in 2023.

Server type	Idle power (W)	Maximum power (W)	Utilization rate (%)	PUE (World average)
Single	82.50	330	15%	2.09
Rack/Computer room	83.50	334	15%	2.46
Midsize DC	97.50	390	40%	1.92
Enterprise DC	122.75	491	50%	1.67
Hyperscale DC (non-AI)	122.75	491	60%	1.18
AI hyperscale DC	736.5	2 946	60%	1.18

Source: Deloitte analysis based on [13], [9], [3], [14], [15].

Table 4. PUE by region in 2023 compared to the world average value.

Region	PUE (%)
World	100%
Asia Pacific	106%
Eastern Europe	92%
Latin America	111%
Middle East and Africa	113%
North America	96%
Western Europe	92%

[1] For hyperscale data centers, PUE is assumed to converge by 2050 toward the current best-in-class data centers, i.e., below 1.10. Smaller, less energy-efficient data centers are considered to converge globally below 1.4, aligning by 2050 with the current or proposed standards for new data centers (Table 5).

Source: Deloitte analysis based on AKCP and Uptime Institute [15], [16].

Table 5. Evolution of servers’ characteristics towards 2050.

Server type	Active idle (W)	Maximum power (W)	Utilization rate (%)	PUE (World average)
Single	66	330	15%	1.40
Rack/Computer room	66.8	334	15%	1.40
Midsize DC	78	390	55%	1.30
Enterprise DC	98.2	491	70%	1.20
Hyperscale DC (non-AI)	98.2	491	70%	1.10
AI hyperscale DC	589.2	2,946	70%	1.10

Source: Deloitte analysis based on [3], [13], [9], [15], [14], [17].

Note: Intermediate values between 2023 and 2050 are obtained through linear interpolation.

2. Supplementary data

2.1 Supplementary information & data on data center's contribution to global GHG emissions

20. The Greenhouse Gas (GHG) emissions associated with data centers considered in the Core Report correspond only to the emissions associated with the operational phase of data centers, specifically those resulting from their electricity consumption (i.e., use stage emissions). Emissions related to equipment production and the construction of data centers are excluded from the analysis. Therefore, this study focuses on Scope 2 GHG emissions, for which a location-based approach is primarily considered (Table 6).

Table 6. **Scope 2 emissions standards based on the GHG Protocol Scope 2 Guidance**

	Location-based	Market-based
Description	Measures GHG emissions from electricity consumption based on the average emissions intensity of the regional or national grid where the data center operates.	Measures GHG emissions based on specific energy procurement choices, such as renewable energy certificates (RECs), guarantees of origin (GOs), or power purchase agreements (PPAs).
Benefits	✓ Provides insight into the regional impact of electricity consumption. ✓ Encourages location in regions with high renewables shares.	✓ Reflects an organization's commitment to renewable energy. ✓ Encourages sustainable energy procurement.
Disadvantage	- Does not reflect proactive renewable energy purchases. - Does not consider hourly operation patterns.	- Complex to track and verify specific energy contracts. - Relies on the availability and credibility of market instruments. - Does not consider hourly operation patterns.

Source: Deloitte's assessment based on GHG Protocol [18].

21. Projected and historic GHG emissions associated with data centers are estimated by multiplying their electricity consumption by the regional electricity grid carbon intensity.

22. For the historical assessment, the regional electricity grid carbon intensity values are calculated using yearly electricity production data provided by Ember [19] for each country and applying the default emission factors from the IPCC Fifth Assessment Report [20] for each production technology. Life-cycle emissions factors have been considered, and include direct emissions, infrastructure and supply chain emissions, and methane emissions (Table 7).

Table 7. **Current emissions of selected electricity supply technology (gCO_2eq/kWh)**

Energy source	Direct emissions	Infrastructure & supply chain emissions	Methane emissions	Total
Coal	760	9.6	47	820(*)
Gas	370	1.6	91	490(*)
Nuclear	0	12	0	12
Solar PV	0	45	0	45
Wind onshore	0	11	0	11
Wind offshore	0	12	0	12
Other renewables	0	24	0	24

Source: Deloitte analysis based on IPCC [20].
(*): Including albedo effect.

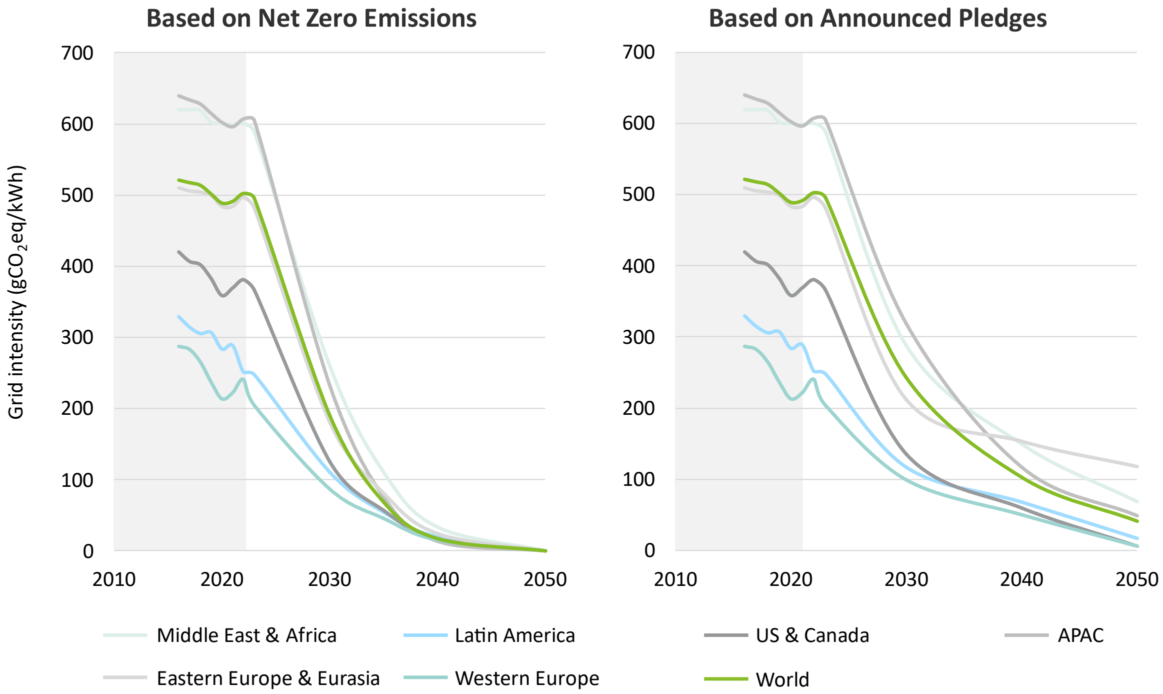
23. Projections of regional electricity grid carbon intensity are calculated based on the foreseen evolution of the energy system in each region and the evolution of default emission factors (Figure 3). The International Energy Agency (IEA) presents multiple scenarios for the evolution of the energy system until 2050, which are used as a basis for determining the electricity mix and grid carbon intensity of each region [21]. The “Net Zero Emissions by 2050 Scenario” outlines a pathway for the future energy landscape to achieve net-zero energy-related CO_2 emissions. The “Announced Pledges Scenario” is less ambitious and assumes that all announced climate commitments will be implemented nationally (Table 8).

Table 8. **World Electricity Generation (TWh)**

	Announced Pledges Scenario			**Net Zero Emissions by 2050**		
	2030	*2040*	*2050*	*2030*	*2040*	*2050*
Total Generation minus power losses	33,623	47,804	61,715	35,321	54,645	71,032
Share of DC demand to total generation in the “High Adoption” scenario	2.9%	5.6%	5.8%	2.9%	4.9%	5.0%
Share of DC demand to total generation in the “Baseline” scenario	2.0%	2.4%	2.7%	1.9%	2.1%	2.4%

Source: [21], [22]

Figure 3. **Evolution of grid carbon intensity (gCO_2eq/kWh)**



Source: Deloitte analysis based on [19], [21].

24. The emissions factors per technology considered align with current value and evolve over time to account for decreased infrastructure and supply chain emissions, as well as lower upstream methane emissions. Thanks to the implementation of best practices, methane leakage are expected to be reduced by 80% in 2050 compared to current values [23], while infrastructure and supply chain emissions are projected to decrease by 95% between 2030 and 2050 [21] (Table 9).

Table 9. **Evolution of emissions of selected electricity supply technology (gCO_2eq/kWh)**

Energy source	Direct emissions	Infrastructure & supply chain emissions				Methane emissions				Total			
	-	2030	2035	2040	2050	2030	2035	2040	2050	2030	2035	2040	2050
Coal	760	6	5	3	0	39	33	19	9	805	798	782	769
Gas	370	1	1	1	0	76	65	36	18	447	435	407	388
Nuclear	0	12	9	6	0	0	0	0	0	12	9	6	0
Solar PV	0	43	32	21	0	0	0	0	0	43	32	21	0
Wind onshore	0	10	7	5	0	0	0	0	0	10	7	5	0
Wind offshore	0	11	8	6	0	0	0	0	0	11	8	6	0
Other renewables	0	24	20	18	0	0	0	0	0	24	20	18	0

Source: Deloitte analysis based on [20], [21].

25. The proportion of data center emissions relative to global GHG emissions is estimated by comparing the calculated data center emissions with total global emissions reported by the United Nations [24] for the year 2022, which is the most recent data available.

26. The carbon budget tracks how much carbon dioxide is emitted into the atmosphere and how much is absorbed or stored by natural processes on land and in the oceans. It helps to assess how much carbon dioxide can still be emitted while limiting global warming to a specific target, such as the 1.5°C or 2°C goals set by the Paris Agreement. The proportion of the remaining carbon budget used by data center operations is estimated by dividing the calculated GHG emissions from data centers by the total remaining carbon budget available to limit global warming to 1.5°C and 1.7°C [25].

2.2 Supplementary information & data on energy savings within data centers

27. Implementation of energy efficiency measures plays a critical role in minimizing the GHG emissions associated with data centers. By reducing electricity consumption, these measures can substantially reduce the overall carbon footprint of data centers. The main levers for improving energy efficiency include (1) improving the PUE, (2) decreasing servers' idle power, (3) increasing computer performance to enhance server efficiency, and (4) increasing data centers' utilization rate [17]. Those four levers have been considered to estimate the reduction in electricity consumption by 2050 (Table 10).

28. In AI hyperscale data centers, energy efficiency gains from improved computing performance could be even greater than those considered in the "High adoption" scenario, especially if hardware improvements continue to follow historical trends [26] and are widely adopted. To evaluate the impact of broader adoption, it is assumed that these improvements will persist at the historical rate until reaching a plateau around 2030 [27]. As data center hardware is typically replaced every four years [28], 25% of the servers are upgraded to the "Best Available Technology" each year.

Table 10. Servers' characteristics with integration of energy efficiency measures in 2050

Server type	Active idle (W)	Additional increase in computer performance*	Utilization rate (%)	PUE (World average)
Single	33	/	30%	1.20
Rack/Computer room	33.4	/	30%	1.20
Midsize DC	39	/	80%	1.20
Enterprise DC	49.1	/	80%	1.20
Hyperscale DC (non-AI)	49.1	/	80%	1.05
AI hyperscale DC	294.6	Performance doubles every 2.69 years until 2030	80%	1.05

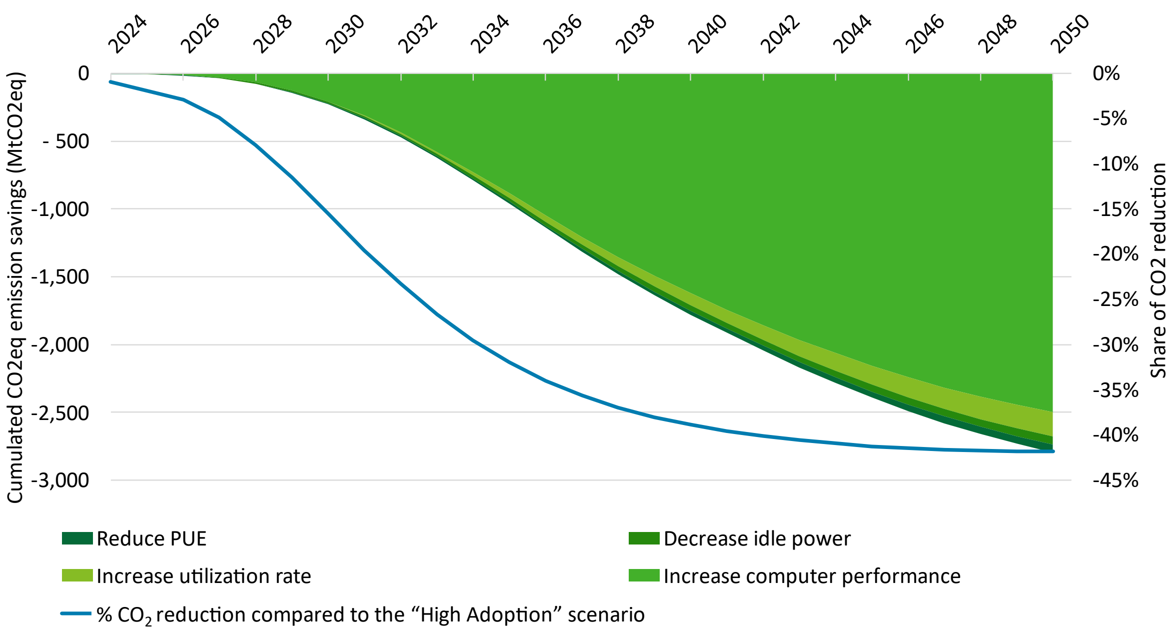
Source: Deloitte analysis based on [3], [13], [9], [15], [14], [17], [27].

Note: Regional PUE are capped at 1, according to the definition of PUE.

(*): Increase of floating-point operations per second (FLOPS) compared to the baseline evolution of servers' characteristics.

29. Energy-efficiency improvements over time are typically non-linear, represented by two improvement rates [12]. The initial breakthrough of energy efficiency improvements is expected to occur between 2023 and 2030. After 2030, further improvements will become more incremental and harder to achieve, however the legacy of the improvements enables a reduction in consumption throughout the entire period. The estimated energy savings lead to reduced GHG emissions associated with the electricity demand from data centers. In the “High adoption” scenario considered in the Core Report, energy efficiency measures enable a cumulative 16% reduction in 2030 and a cumulative 42% reduction in 2050 in CO_2eq (Figure 4).

Figure 4. **Cumulated CO_2eq emission savings through efficiency improvements, 2024-2050, “High Adoption” scenario**

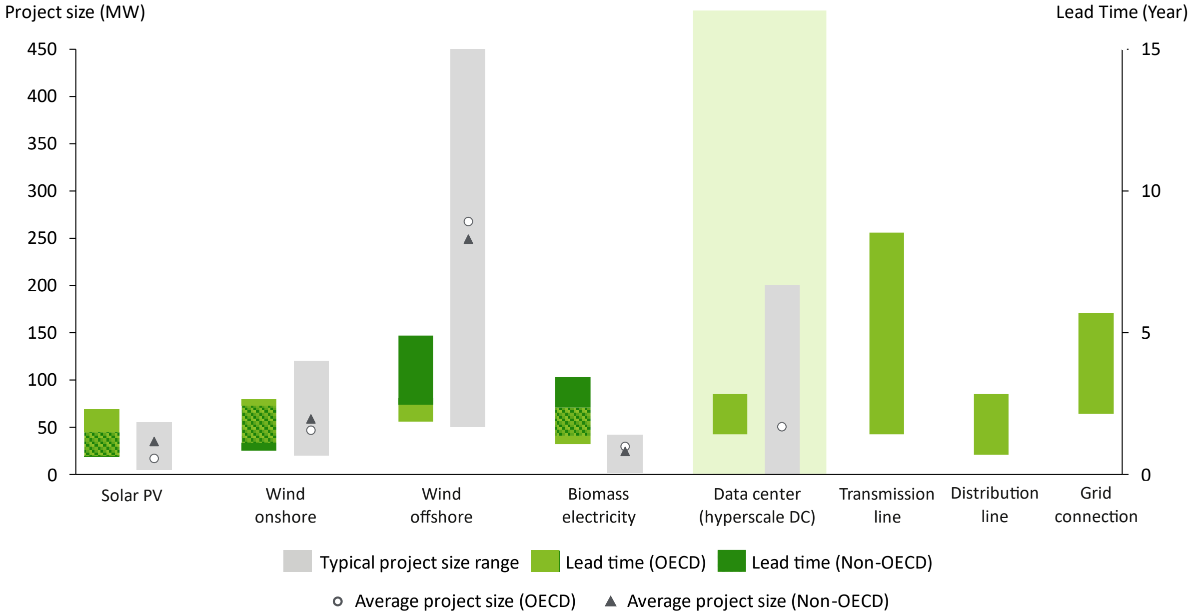


Source: Deloitte analysis

2.3 Supplementary data on renewable development and grid assets lead time

30. To estimate to risks of bottlenecks associated with data center electricity consumption, a benchmark of typical project sizes and lead times for renewable electricity production, grid developments, and data center projects has been performed (Figure 5).

Figure 5. **Typical project size and lead time for renewable, data center and grid development**



Source: Deloitte analysis based on [29], [30], [31], [32], [33], [34], [35].

31. Currently, the average time to deploy large-scale onshore wind, solar PV, or biomass electricity projects is comparable to the average time needed to build data centers. Offshore wind projects present slightly longer lead times but offer larger capacities, which can substantially contribute to meeting data centers' electricity demand. This analysis shows that lead times for building new renewable capacities are not yet a threat to their concurrent development with data centers.

32. Conversely, the analysis suggests that the reinforcement of the electricity grids and the rapid connection to these networks are emerging as potential bottlenecks. Electricity grid infrastructure, particularly transmission lines, presents extended lead times. Grid connection times also appear significantly long, therefore threatening the timely development of both renewable electricity production assets and data centers. This phenomenon is fueled by growing backlogs in grid connection requests worldwide [36], [37].

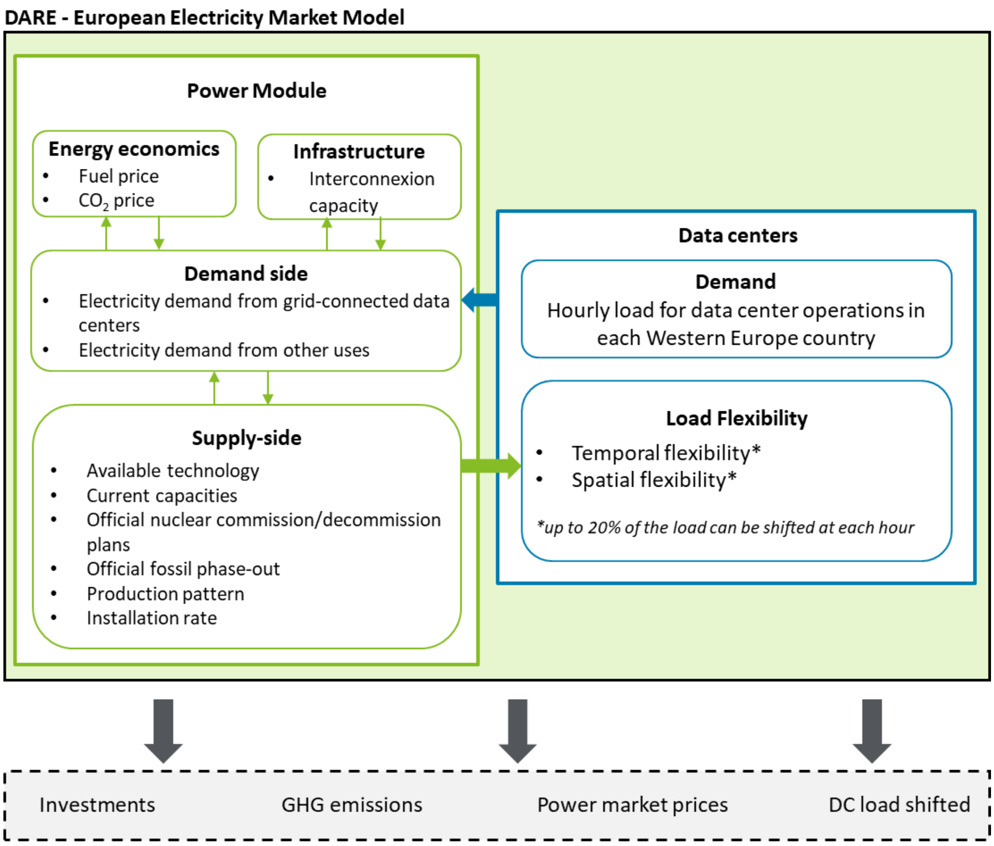
3. The DARE Model

33. Ex-post analyses are performed thanks to Deloitte's in-house energy model DARE (Deloitte Applied Research on Energy), which includes a module dedicated to the representation of the European power system (Figure 6).

34. DARE consists of a mixed-integer linear programming model that performs a least-cost optimization of the investment and the operations of the energy system. Starting from current installed capacities, the model iteratively simulates the period from 2025 to 2050 with a 5-year timestep and without perfect foresight. Based on the total electrical load, i.e., the electrical load from both data centers and all other sectors, the model endogenously decides the commissioning or decommissioning of generation units. Regional specificities are considered through renewable potential and production patterns as well as planned capacity such as official nuclear commission and decommission plans and announced fossil phase-out. Further information and model description can be found in the literature [38], [39].

35. Spatio-temporal load shifting is included within the modeling framework, allowing for the flexible dispatch of 20% of the data center load hourly. Additionally, constraints are applied to ensure that the total data center load is met by the end of each day.

Figure 6. Model logic framework for the European Electricity Market module of DARE



Source: Deloitte

4. Green AI policy applicable to data centers

36. Numerous metrics are used to measure the efficiency of data centers, often overlapping and addressing different aspects of resource use and performance. The number of metrics makes it challenging to pinpoint the most relevant measures and compare and benchmark different regulations. Furthermore, each metric has limitations and cannot capture all efficiency aspects. These metrics and associated regulations form the foundation of the "Set efficiency standards & foster transparency" pillar in Figure 9 of the Core Report. The most widely used and pertinent metrics are described in Table 11, while Table 12 provides an overview of key existing regulations related to these metrics. Based on our assessment, PUE is by far the most legislated upon metric for data centers and, as such, is at the center of nearly all regulations concerning data centers. The utilization rate is another standard metric for measuring the efficiency of data centers.

Table 11. Key metrics on data center efficiency

Metric	Formula	Description
Power Usage Effectiveness (PUE)	$= \frac{Total\ Data\ Center\ Electricity\ Use}{IT\ equipment\ Electricity\ Use}$	A lower value means a more efficient data center, with a theoretical minimum of 1.0 where all the data center's electricity is used by the IT equipment. Larger data centers typically have a lower PUE [40]. Factors that negatively impact the PUE include energy intensive cooling and lighting. PUE has its limitations; it does not account for the efficiency of the IT equipment itself and can vary due to external factors such as climate.
Utilization Rate	$= \frac{Actual\ Power\ Consumption}{Total\ Power\ Capacity}$	A higher value means a more efficiently used data center with a theoretical maximum of 1 where all IT equipment is used at full capacity. Larger data centers typically have higher utilization rates. Factors negatively impacting the utilization rate include underutilized server capacity, which is often caused by redundancy. Even at idle state, server equipment consumes electricity, highlighting the importance of a high utilization rate to limit electricity consumption.
Water Usage Effectiveness (WUE)	$= \frac{Data\ Center\ Water\ Use}{IT\ equipment\ Electricity\ Use}$	WUE is the standard metric for measuring the water usage intensity of a data center. Water is mostly used for cooling purposes. A lower value indicates a more water-efficient data center with the theoretical minimum being 0 where no water is being used. Factors negatively impacting WUE include water-intensive cooling systems and limited water recycling practices. WUE has limitations, like not considering the source and sustainability of the water used and the variability in measurements due to external factors such as climate and local water availability.
Energy Reuse Factor (ERF)	$= \frac{Reused\ heat\ energy}{Total\ Data\ Center\ Electricity\ Use}$	The higher the ERF, the more waste heat a data center recovers and reuses. Data center waste heat can be used to heat nearby buildings, be fed into district heating systems or heat swimming pools and recreational facilities [41]. Other variations of ERF are

		sometimes used like Energy Reuse Effectiveness (ERE) which considers net energy use after accounting for reused energy.
Cooling Efficiency Ratio (CER)	$= \frac{Total\ Cooling\ Output}{Total\ Power\ for\ Colling\ Output}$	This standard metric measures the effectiveness of a data center's cooling system. A higher CER indicates a more efficient cooling system.
Renewable Energy Factor (REF)	$= \frac{Renewable\ Energy\ Consumption}{Total\ Data\ Center\ Electricity\ Use}$	This standard metric measures the proportion of a data center's total electricity consumption from renewable energy sources. A higher REF indicates a more significant percentage of the data center's energy coming from renewable sources.

Table 12. Selected example of policy and certification on data center efficiency

Metric	Regulatory and certification benchmarks
Power Usage Effectiveness (PUE)	**China** PUE<1.5 for new DC, <1.3 for large DC. Cities also imposed local rules, going as low as PUE<1.15 in Beijing [17], [42].
	Singapore PUE<1.3 for new DC [17].
	France Maximum PUE requirement between 2.0 to 1.2 for all DC, depending on the size, by 2030 [17].
	Germany PUE<1.5 by 2027 and <1.3 by 2030 for all DC. PUE<1.2 for new DC by 2026 [17], [43].
	Japan All DC operators must work towards a PUE<1.4 [17].
	UK Rebate on Carbon Tax for regular predefined reductions in PUE over two-year periods [17].
	EU Voluntary agreement: PUE<1.4 for DC starting in 2025 and for all DC in 2030 [17].
	Australia, Austria, EU, Germany, Singapore, others PUE used for various labels and certification schemes (Ecolabels, Codes of Conduct, etc.) [17].
	Australia, California, EU, Germany, Netherlands, US PUE used as a decision factor in public sector DC procurement [17].
Utilization Rate	**China** Utilization rate>60% for new DC [17].
	Germany, Austria CPU utilization rate>20% to achieve Blue Angel (DE) / Ecolabel (AT) data center certification [17].
Water Usage Effectiveness (WUE)	**San Jose (California)** DC required to meet specific predefined WUI targets. In 2022, that target was 772.42 liters/m² [44].
	EU WUE<0.4l/kWh for new DC by 2025 in areas with water stress, for the Signatories of the Climate Neutral Data Centre Pact [45].
	Singapore Big DC required to report WUE. WUE reduction target over the next 10 years: from 2.2l/kWh to 2l/kWh [46].

	Germany, Austria Mandatory WUE annual reporting to achieve Blue Angel (DE) / Ecolabel (AT) certification [47], [48].
Energy Reuse Factor (ERF)	**Germany, Austria** ERF>0 to achieve Blue Angel (DE) / Ecolabel (AT) certification [47], [28].
	Germany ERF>0.1, ERF>0.15 and ERF>0.20 for DC starting operation after 2026, 2027 and 2028 respectively [43].
Cooling Efficiency Ratio (CER)	**Germany, Austria** CER>9 to achieve Blue Angel (DE) / Ecolabel (AT) certification [17].
Renewable Energy Factor (REF)	**EU** REF used as a decision factor in public sector DC procurement: mandatory REF disclosure and preference for REF=1, using a market-based approach [49].
	China Annual 10% increase in REF by 2025 [50].
	Germany REF>0.5 from 2024 and REF=1 by 2027, using a market-based approach [43].

37. In addition to efficiency standards, additional policies can be considered to mitigate the potential negative environmental and energy impacts of data centers. Table 13 details the main policy elements presented in Figure 9 of the Core Report, focusing on the three other pillars "Promote clean energy supply", "Plan suitable location" and "Incentivize efficient operations". Examples of existing regulations specifically targeting data centers are provided, or, in the absence of such regulations, similar regulations from other sectors are included for reference.

Table 13. Policy blueprint supporting Green AI

Item	Description	Selected example policies
	Promote clean energy supply	
Enforce granularity of energy certificates	Detailed and specific Guarantees of Origin (GOs) for electricity enables to enforce spatial and temporal matching of demand and generation.	**EU** Granular GOs are enabled and encouraged by the Renewable Energy Directive [51]. **Turkey, Taiwan, China, Japan, Korea** Renewable energy certificate (REC) are put in place to increase the use of renewable energy sources [52].
Set additionality requirement	Strict additionality criteria means ensuring that the renewable energy sourced is fulfilled by new renewable capacity that would not have existed without the data center's investment.	**EU** Additionality criterion is required for the production of renewable hydrogen. It ensures that PPAs are fulfilled by new rather than existing renewable capacities by 2028 [53].
Set geographical correlation requirement	Geographical correlation measures the alignment between the locations of data centers and the sources of renewable energy they use.	**EU** Geographical correlation criterion is required for the production of renewable hydrogen. It ensures that the renewable electricity claimed to supply the demand is produced in the same bidding zone as the consumption [53].

Set temporal correlation requirement	Temporal correlation measures the alignment between the timing of renewable energy generation and the electricity consumption patterns of data centers.	**EU** Temporal correlation criterion is required for the production of renewable hydrogen. It ensures that hydrogen production matches renewable energy sources production. Until 2030, a monthly correlation is required. From 2030, a hourly correlation is required [53].
Mandate on-site RES	The strategic placement of data centers near renewable energy generation facilities allows them to cover part of their electricity demand from sustainable sources. This approach reduces carbon emissions and reliance on the grid, and minimizes transmission losses.	**France** PV coverage must exceed 30% of the roof of any new commercial buildings with a surface>500m^2. This will increase to 50% by 2027 and will extend to existing commercial buildings by 2028 [54].
		California PV coverage must exceed 15% of the roof of any commercial building [55].
		Taiwan New buildings shall install solar photovoltaic power generation facilities, installation capacities depend on building range and light receiving conditions [56].
	Plan suitable location	
Publish grid hosting capacity map	Publicly accessible maps that detail the capacity and availability of the electricity grid infrastructure across different regions provide information on areas where the grid can support new developments, including data centers, by showing the current state of infrastructure, available capacity, and potential constraints.	**US** Utilities in 26 states publish grid hosting maps [57].
		EU DSOs/TSOs are required to publish highly spatially granular information on capacity for new connections. Many utilities already publish maps [57].
Implement nodal electricity pricing	Nodal electricity pricing refers to a system where electricity costs are determined based on a specific location within the grid. This system accounts for the varying costs of generating and delivering electricity to different nodes or locations, providing high granularity. Electricity prices better represent local supply and demand, transmission constraints, and generation costs, leading to more accurate pricing signals and potentially more efficient energy usage.	**Canada, US (not all states), New Zealand, Chile** Nodal electricity pricing is already implemented [58], [59].
Allow private wire	Private wiring consists of allowing private entities to install, operate, and own their electricity production infrastructure to directly connect data centers with an energy source "behind the meter", bypassing the national electricity grid.	**Ireland** The country is in the process of legalizing private wire connections between renewable energy sources and DC [60], [61].
Mandate areas for data centers	Distribution System Operators (DSOs), Transmission System Operators (TSOs), and local municipal authorities can collaborate to designate and agree upon specific areas for the development of data centers. This ensures that data centers are strategically	**Netherlands** Hyperscale DC development is limited to areas with ample space and abundant clean energy. Amsterdam has further significantly restricted most DC development due to space constraints and to avoid grid congestion [62].

	located based on infrastructure capacity, energy availability, and environmental factors such as climate or water impact.	**Ireland** A de facto moratorium on DC has been imposed until 2028 by restricting new DC connections to the grid [63].
	Incentivize efficient operations	
Implement dynamic electricity pricing	Electricity tariffs can vary based on real-time factors such as demand, supply, and market conditions. This is referred to as dynamic tariffs and encourages more efficient use of energy aligned with periods of lower market demand or higher renewable energy availability. Tariffs can also vary based on consumer-specific criteria, such as charging higher electricity tariffs to inefficient data centers. This is referred to as targeted price hikes and can incentivize efficient data center operations.	**China** The city of Beijing charges fixed electricity tariff surcharges for data centers with a PUE>1.4 and >1.8, which correspond to approximately a 40% and 100% higher electricity price increase, respectively [42]. **Australia, EU, US** Dynamic tariff programs are already in place [64].
Frame green software design and green computing	Green software development focuses on creating energy-efficient software and minimizes resource consumption throughout its lifecycle, for example by encouraging developers to optimize code for efficiency. Green Computing involves designing and using hardware and infrastructure to reduce electricity consumption and enhance sustainability, for example by adopting energy-efficient hardware.	**Singapore** The country is in the process of introducing guidelines for green software development [46]. Dozens of global norms, standards, and certifications already govern hardware's energy efficiency.
Enforce industrial demand response programs	Demand response programs incentivize industrial facilities, including data centers, to be flexible and actively participate in adjusting or reducing electricity consumption during periods of high demand or limited energy supply. This flexibility contributes to grid stability and reliability.	**EU, UK, US, Brazil, Colombia, Australia** Demand response programs are already in place [65], [66], [67].
Mandate Energy Management Systems	Energy Management Systems (EMS) enable to systematically monitor, control, and optimize energy usage through processes and technologies. It improve efficiency, reduce costs, and minimize environmental impact.	**EU** EMSs will become an obligation for large energy consumers, including larger DC [68]. **Germany** EMSs will be required for large DC by 2026 [43]. **China** Connected EMS are mandated for larger DC in the city of Beijing [42].

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