Not All Doom and Gloom: How Energy-Intensive and Temporally Flexible Data Center Applications May Actually Promote Renewable Energy Sources

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Appendix (available online via http://link.springer.com)

Appendix A – Detailed model development

Let us introduce relevant variables referring to Glenk and Reichelstein (2019) (see Appendix B). In particular, the variable k_e constitutes the installed (peak) capacity of the RES-plant and may be scaled to fit the size of a specific plant setup. k_{DC} correspondingly depicts the (peak) capacity of the DC. The capacity factor $CF(t)$ describes how much of the capacity is generated by the plant at any given time *t* that dependents on the operation mode and the intermittency of the RES. $p_b(t)$ constitutes the price that is paid for buying electricity from the market, whereas $p_s(t)$ constitutes the price that is obtained when selling electricity at the market. Note that the two prices may be identical. We assume that the no arbitrage condition holds on the electricity market for positive electricity prices: $p_b(t) > p_s(t)$ and $p_s(t) > 0$ at any given time period. The RES-plant may be switched off at no costs, such that the RES-plant is idled if the price for selling electricity falls below 0. We further define the conversion value of the DC, CV_{DC}, as the value that is obtained when consuming 1 kWh of electricity to execute computations minus corresponding variable costs aside of the consumed electricity. While previous work considers a fixed price determination of the energy-consuming part of the IES, we develop the model: we reflect both, the conversion rate η that describes how much computational DC output is generated per consumed kWh and the price of the output p_{DC} not to be time-constant (although constant rates may still be incorporated). First, η is based on the constant device-specific performance of the processing unit per electricity input λ. This parameter λ depicts the FLOPS, i.e., floating operations per second, or hash rate per second and per kW based on the specific application. Second, η further incorporates the variable conversion rate $\varphi(t)$ of these basic computing operations into the DC output that has a (time-varying) price on a computing power market $p_{DC}(t)$. Thus, η allows to realistically reflect, for example, the energy-intensive cooling based on various, changing surrounding temperatures, which influence the internal energy consumption of a DC (Torell et al. 2015) or the time-varying difficulty when mining cryptocurrencies (Nakamoto 2008) (cf. Section 4):

$$\eta(t) = \lambda \cdot \varphi(t) \tag{1}$$

For p_{DC}, this allows us to reflect the fact that cloud computing capacities may be traded under spot market-like conditions with time-varying prices (Zhang et al. 2011b). Furthermore, we note that the consideration of η and p_{DC} not being time-constant also allows us to reflect specific cases in which η and p_{DC} would be time-constant, easily. Accordingly, we define a time-varying conversion value of the DC, $CV_{DC}(t)$, that is characterized by a time-dependent conversion efficiency $\eta(t)$ and the price obtained for the output of the DC, $p_{DC}(t)$:

$$CV_{DC}(t) = \eta(t) \cdot p_{DC}(t) \tag{2}$$

The contribution margin (CM) of a stand-alone DC at time *t*, depending on the chosen capacity k_{DC} that may only purchase electricity on the open market is then defined by:

$$CM_{DC}(t|k_{DC}) = [CV_{DC}(t) - p_b(t)] \cdot k_{DC} \tag{3}$$

Using the IES, the operator maximizes the periodic CM given the investment in the system. We identify four cases with respect to the CM of the IES: As these cases may arise at any point of time, we introduce them as the operation modes of the IES. The four modes represent the specific operation modes of the IES, based on the economic influencing factors as displayed in Figure 2. In mode 1, RES electricity is sold on the electricity market for the price $p_s(t)$, i.e., the DC is idled since a conversion is not economically viable and $p_b(t) \geq p_s(t) \geq CV_{DC} \geq 0$ holds. Thus, the CM in this mode only depends on the variables that can be attributed to the RES-plant, denoted by CM_1 and the index representing the respective mode:

$$CM_1(t|k_e) = p_s(t) \cdot CF(t) \cdot k_e \tag{4}$$

Referring to Glenk and Reichelstein (2019), we elaborate Figure 2 while enhancing it with the time-variant conversion value of the DC to illustrate the four modes. In mode 2, the buying price for electricity exceeds the conversion value of the DC, which, in turn, exceeds the selling price: $p_b(t) \geq CV_{DC}(t) > p_s(t) \geq 0$. The electricity generated by the RES-plant is thus consumed in the DC as this yields a positive CM. No additional electricity is bought from the electricity market. The maximum conversion capacity k_e as well as the specific capacity factor $CF(t)$ limit the conversion in this mode, which is captured by the variable $\text{z}(\text{t}|k_e, k_{DC}) = \min\{CF(t) \cdot k_e, k_{DC}\}$. As costs for switching the DC on and off are assumed to be zero in this work, the CM in mode 2 follows the relationship:

$$CM_2(t|k_e, k_{DC}) = p_s(t) \cdot CF(t) \cdot k_e + [CV_{DC}(t) - p_s(t)] \cdot \text{z}(\text{t}|k_e, k_{DC}) \quad (5)$$

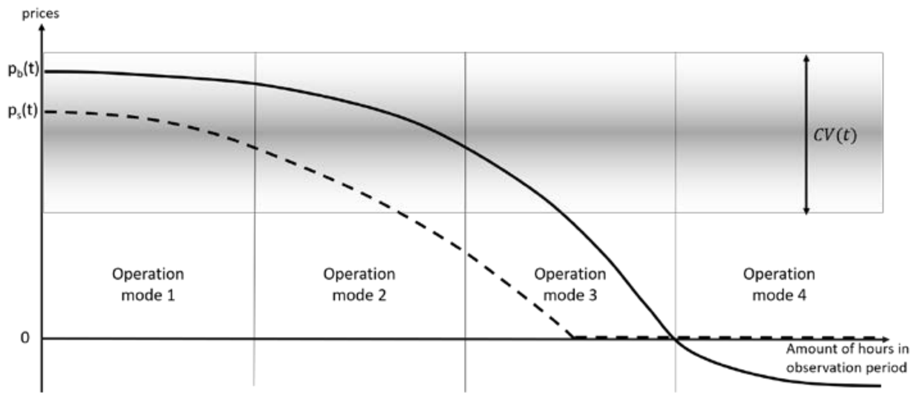

Figure 1. Operation modes of the IES

In mode 3, both electricity prices are non-negative and lower than the conversion values of the DC: $CV_{DC}(t) > p_b(t) \geq p_s(t) \geq 0$. Hence, it is optimal to consume the generated electricity from the RES-plant in the DC, and furthermore, any idle capacity of the DC is powered with electricity bought from the electricity market, such that the DC operates at full capacity. The CM is then described by the sum of the stand-alone plants and the conversion premium of consuming generated electricity from the RES-plant in the DC:

$$\begin{aligned} CM_3(t|k_e, k_{DC}) = {} & p_s(t) \cdot CF(t) \cdot k_e \\ & +[CV_{CP}(t) - p_s(t)] \cdot \text{z}(\text{t}|k_e, k_{DC}) \\ & +[CV_{DC}(t) - p_b(t)] \cdot [k_{DC} - \text{z}(\text{t}|k_e, k_{DC})] \end{aligned} \quad (6)$$

In mode 4, the RES-plant is shut down, as $CV_{DC}(t) \geq p_s(t) = 0 > p_b(t)$, and electricity from the grid is again used to operate the DC at full capacity resulting in the following CM based on the characteristics of the DC alone:

$$CM_4 = [CV_{DC}(t) - p_b(t)] \cdot k_{DC} \quad (7)$$

The overall CM of the IES can be written in the following way:

$$\begin{aligned} CM(t|k_e, k_{DC}) = {} & p_s(t) \cdot CF(t) \cdot k_e \\ & +[p_{b+}(t) - p_b(t)] \cdot k_{DC} \\ & +[p_+(t) - p_s(t)] \cdot z(\text{t}|k_e, k_{DC}), \end{aligned} \quad (8)$$

where $p_{b+}(t) = max\{p_b(t), CV_{DC}(t)\}$ and $p_+(t) = max\{min\{p_b(t), CV_{DC}(t)\}, p_s(t)\}$.
This illustrates that the CM of an IES can be expressed as the sum of the CMs of the two stand-alone energy systems plus a third term that captures the economic interaction of the two parts of the system. The term $p_{b+}(t) - p_b(t) = max\{CV_{DC} - p_b(t), 0\}$ is referred to as the conversion premium of the DC. It reflects the option of the DC to idle its operation at times when the buying price of electricity exceeds

the conversion value of DC. The latter term of the equation reflects potential synergies, i.e., the benefit of consuming the generated electricity internally.

We now further calculate the NPV of the IES. Here, we refrain from detailing out the further calculations introduced in Glenk and Reichelstein (2019), but we summarize the approach briefly: we use the levelized costs of electricity (LCOE) that are calculated based on the average capacity factor of the RES-plant. We furthermore employ a tax factor with respect to depreciation of investment costs and the corporate tax rate $\boldsymbol{\alpha}$. As $CF(t)$ and $p_s(t)$ vary in real-time, their values are captured as the multiplicative deviation of their mean that is indicated by an overline above the respective variable. Γ^s describes the covariance of the multiplicative deviations of $CF(t)$ and $p_s(t)$ with m accounting for the number of hours in the observation period:

$$\Gamma^s = \frac{1}{m}\int_0^m \frac{CF(t)}{\overline{CF}} \cdot \frac{p_s(t)}{\bar{p}_s} dt \tag{9}$$

The stand-alone NPV of the RES-plant is then calculated as:

$$NPV(k_e, k_{DC}) = (1-\alpha) \cdot L \cdot [(\Gamma^s \cdot \bar{p}_s - LCOE) \cdot \overline{CF} \cdot k_e \tag{10}$$

L describes the levelization factor that distributes the respective costs to the discounted number of hours over the lifetime of the plant-based on the degradation of the system x^{i-1} and the assumed weighted average cost of capital (WACC):

$$L = m \cdot \sum_{i=1}^{T} x^{i-1} \cdot \frac{1}{WACC}^{i} \tag{11}$$

The fixed costs associated with electricity generation are levelled to an hourly basis. We further introduce the concept of levelized fixed costs of computing power LFCCP, which capture the fixed costs of consuming one kWh electricity in the DC. The relevant variable costs based on the consumed electricity are already considered by the CM. The concept is based on the well-known formalization of levelized costs of electricity (LCOE) for electricity generating plants:

$$LFCCP = \frac{\sum_{i=1}^{T} F_{DCi} \cdot \gamma^i}{L} + \frac{SP_{DC}}{L} \tag{12}$$

F_{DCi} constitutes fix (maintenance) costs in period i, whereas γ discounts the respective costs based on the WACC, while SP_{DC} constitutes the system price of the DC. Hence, the NPV of an IES as our objective function writes as follows (overlines again indicate the mean):

$$\begin{aligned} NPV(k_e, k_{DC}) = (1-\alpha) \cdot L \cdot [&(\Gamma^s \cdot \bar{p}_s - LCOE) \cdot \overline{CF} \cdot k_e \\ &+(\bar{p}_{b+} - \bar{p}_b - LFCCP) \cdot k_{DC} \\ &+(\bar{p}_+ - \bar{p}_s) \cdot z(k_e, k_{DC})] \end{aligned} \tag{13}$$

Equation (13) reflects the stand-alone values of the specific parts of the IES by its first two terms as well as the synergistic value by the last term. Thus, the last term in Equation (13) allows us to state that the integration of an energy-intensive DC may well increase the NPV of an RES-plant as a part of the IES. The synergistic value is based on the fact that costs, e.g., transmission and storage costs, associated with the consumption of electricity from the market may be avoided. This is in line with the findings of Glenk and Reichelstein (2019) since these costs may be identified as the difference between $p_b(t)$ and $p_s(t)$ in mode 3. Furthermore, the consumption of the DC increases as it also operates economically viable, if $p_b(t) \geq CV_{DC}(t) \geq p_s(t)$ represented by mode 2. Hence, our model analytically illustrates that investments in IES, and therefore in RES-plants may increase, as their NPV increases when they are integrated with a DC.

Appendix B – Model variables

Model variable	Description	Unit
NPV	Net present value	€
k_e	RES plant peak capacity	MW
k_{DC}	DC peak capacity	MW
$CF(t)$	Capacity factor of the RES plant	$[-]$
λ	Processing power	$FLOPS/_{kW}$
$\varphi(t)$	Computing conversion rate	$[-]$
$\eta(t)$	DC conversion rate	$DC\ Output/_{kWh}$
$CV_{DC}(t)$	Conversion value of DC	$€/_{kWh}$
$CM(t\|k)$	Contribution margin given k	$€/_{kWh}$
$z(t\|k_e, k_{DC})$	CF auxiliary variable	$[-]$
$p_{b+}(t), p_{+}(t)$	Auxiliary price variables	$€/_{kWh}$
α	Corporate tax rate	$[-]$
Γ^s	Covariance of multiplicative deviation	$[-]$
L	Levelization factor	$[-]$
$LFCCP$	Lev. fixed cost of computing power	$€/_{kWh}$

Appendix C – Input parameters for ML case

Evaluation parameters	Unit	Value used for evaluation	Source
Capacity factor of RES, $CF(t)$	$[-]$	$Ø = 42\%$	Capacity factor of incumbent onshore wind power stations in Northern Germany according to: Renewable.ninja data; available at: www.renewables.ninja
Electricity buying price, $p_b(t)$	$€/_{kWh}$	$Ø = 0.054$	EPEX intraday spot data for years 2016-2018; data is publicly available but subject to licensing at: www.epex-spot.com/en/market-data; additional fee in line with Glenk and Reichelstein (2019)
Electricity selling price, $p_s(t)$	$€/_{kWh}$	$Ø = 0.036$	EPEX intraday spot data for years 2016-2018; data is publicly available but subject to licensing at: www.epex-spot.com/en/market-data
DC output price, $p_{DC}(t)$	$€/_{\text{Instance} * \text{h}}$	23.36	Assumption based on: AWS E2 on-demand prices; available at: www.aws.amazon.com/ec2/pricing/
Levelized cost of electricity, LCOE	$€/_{kWh}$	0.0483	In line with Glenk and Reichelstein (2019)
Tax rate, $\boldsymbol{\alpha}$	$[-]$	30%	Corporation tax, Germany
System degradation factor, x^i	$[-]$	95%	Assumption based on: www.datacenterdynamics.com/en/analysis/the-data-center-life-story/
Weighted average cost of capital, $WACC$	$[-]$	8%	Assumption in line with, e.g., Glenk and Reichelstein (2019)
Fixed cost of operating a DC, F_{DCi}	$€/_{kW * a}$	3,000	Assumption based on Popa et al. (2010)
System price for the DC, SP_{DC}	$€/_{kW}$	40,000	Assumption based on Intel Xeon 8175 specifications; available, e.g., at: www.wikichips.org

Appendix D – Input parameters for Bitcoin mining case

Evaluation parameters	Unit	Value used for evaluation	Source
Capacity factor of RES, $CF(t)$	$[-]$	$Ø = 42\%$	Capacity factor of incumbent onshore wind power stations in Northern Germany according to: Renewable.ninja data; available at: www.renewables.ninja
Electricity buying price, $p_b(t)$	$€/_{kWh}$	$Ø = 0.054$	EPEX intraday spot data for years 2016-2018; data is publicly available but subject to licensing at: www.epex-spot.com/en/market-data; additional fee in line with Glenk and Reichelstein (2019)
Electricity selling price, $p_s(t)$	$€/_{kWh}$	$Ø = 0.036$	EPEX intraday spot data for years 2016-2018, data is publicly available but subject to licensing at: www.epex-spot.com/en/market-data
DC output price, $p_{DC}(t)$	$€/_{฿}$	$Ø = 3.472$	BTC chart; available, e.g., at: www.blockchain.com/
DC computing power, λ	$Hash/_{s * kW}$	$1.9 * 10^{19}$	Antminer S5 specifications; available, e.g., at: www.antminerdistribution.com/antminer-s5/
DC conversion efficiency, $\varphi(t)$	$1/_{Hash/_{s}}$	$1.2 * 10^{-22}$	BTC chart; available, e.g., at: www.blockchain.com/
Levelized cost of electricity, LCOE	$€/_{kWh}$	0.0483	In line with Glenk and Reichelstein (2019)
Tax rate, $\boldsymbol{\alpha}$	$[-]$	30%	Corporation tax, Germany
System degradation factor, x^i	$[-]$	95%	Assumption based on Bitcoin online forums, e.g., www.Bitcointalk.org/
Weighted average cost of capital, $WACC$	$[-]$	9%	Assumption in line with, e.g., Glenk and Reichelstein (2019)

Fixed cost of operating a DC, F_{DCi}	$€/_{kW * a}$	15	Assumption in line with Bitcoin online forums, e.g., www.Bitcoint-alk.org/
System price for the DC, SP_{DC}	$€/_{kW}$	870	Assumption based on Antminer S5 specifica-tions; available, e.g., at: www.antminerdistribu-tion.com/antminer-s5/
Block reward, $BR(t)$	$฿/_{Block}$	12.5	BTC chart; available, e.g., at: www.block-chain.com/
Transaction fee, TF(t)	$฿/_{Block}$	0.5	BTC chart; available, e.g., at: www.block-chain.com/
Management fee, MF	$[-]$	1,5%	Assumption in line with Bitcoin trading platform information; available, e.g., at: www.block-chain.com/