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Data Centres' Power Profile Selecting Policies for Demand Response: Insights of Green Supply Demand Agreement

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Abstract

Demand Response mechanisms serve to preserve the stability of the power grid by shedding the electricity load of the consumers during power shortage situations in order to match power generation to demand. Data centres have been identified as excellent candidates to participate in such mechanisms. Recently a novel supply demand agreement have been proposed to foster power adaptation collaboration between energy provider and data centres. In this paper, we analyse the contractual terms of this agreement by proposing and studying different data centres' power profile selecting policies. To this end, we setup a discrete event simulation and analysed the power grid's state of a German energy provider. We believe that our analysis provides insight and knowledge for any energy utility in setting up the corresponding demand supply agreements.

Keywords: Demand response, data centre power profiles, selecting policy, green supply demand agreement

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1. Problem statement

Few will doubt that the power grid is a critical infrastructure, which directly affects many aspects of modern life. Conventionally, the power grid's stability can be characterised by three different operational states: *Normal*, *mission-critical* and *emergency*. In normal state, the grid is operating under usual conditions, whereas during mission-critical state, the power grid

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is still operational, however the power demand is high bringing the grid to its limits. Emergency state refers to the fact that a blackout occurred causing parts or the whole power grid to break down. In other words, the above mentioned three states correspond respectively to the following three grid-scale scenarios: Daily time/cost-optimized, day-ahead/day-off price or reliability, and ancillary services and emergency. Nowadays, with the advent of renewable energy sources (e.g. photovoltaic), the major challenge is to keep the stability of the power grid (prevent blackouts to happen), and hence preserve normal operational state, by matching the power generation to demand.

Recently, Demand Response (DR) mechanisms have been proposed within the context of "Smart Grid" in order to preserve the stability of power grid – hence to cope with the sudden changes of power demand and generation. The main objective of such mechanisms is to match power generation to demand by changing the electricity load of the consumers in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [1]. Lately, data centres have been investigated for their participation in DR mechanisms [2; 3]. It was shown that they are good candidates due to their highly automated infrastructure as well as significant energy usage. To this end, a novel supply demand agreement for power adaptation collaboration between energy provider and data centres was proposed by [4], which defines power relevant contractual terms for both parties. Furthermore, based on the proposed terms, the authors introduced a "fair" power profile selecting policy. In short, whenever the energy provider detects a shortage/surplus situation, it requests from the participating data centres for their collaboration. Every data centre, upon receiving such a request, sends back either a *negative acknowledgment* or at least one *power profile.* The former case denotes that the data centre is refusing to collaborate whereas in the latter case, based on its local power adaptation flexibilities (e.g. running data centre on UPS or own diesel generator, shifting/shedding workload to reduce power consumption, heating up/cooling down the data centre, etc.), the data centre sends back to energy provider one or more power profiles. After receiving all the profiles, the energy provider needs to apply a *power profile selecting policy* in order to choose appropriately profiles of different data centres to fulfil its needs in terms of shortages/surplus. The authors of [4] called the proposed selecting policy "fair" due to the fact that the burden of power adaptation collaboration is distributed fairly among the data centres.

In this paper, we analyse the power adaptation collaboration between the energy provider and data centres by taking into account the different contractual terms of the proposed supply demand agreement of [4]. For this purpose, in addition to the *fair* power profile selecting policy, we introduce two new policies namely *cost-saving* and *peak-avoidance.* The former policy is used in order to minimise the cost that energy provider needs to pay as incentive to data centres for the carried out adaptation, whereas the latter is devised to circumvent any power grid instability by avoiding power peaks that might happen during the recovery phase of the performed adaptation. Consequently, we setup a discrete event simulation and analysed the power grid's state of a German energy provider E-on[1] in 2011. We identified power shortage situations and conducted power adaptation collaboration using the aforementioned three different policies, where 15k data centres were involved with different sizes and power adaptation capabilities. The policies were compared by taking into account different metrics derived from the proposed supply demand agreement of [4]. The results show that each of the studied three policies has its own advantages and inconveniences based on the examined circumstances. We believe that the obtained results contribute as providing insights not only to *energy utilities* in setting up DR programs with data centres but also to *regulatory bodies* (e.g. US Federal Energy Regulatory Commission) who play a key role in formulating DR mechanisms and energy market design. It is worth pointing out that in this paper we don't differentiate between numerous stakeholder of the energy market such as Distribution System Operator (DSO), Transmission System Operator (TSO), and Energy Service Provider (ESP) and use only Energy Provider to refer any of the above mentioned stakeholder. Also, the power adaptation collaboration between data centre and its IT customers concerning Service Level Agreements is out of the scope of this document and interested readers can refer to [5; 6].

The rest of this paper is organised in the following manner: Section 2.1 presents the architectural overview of the power adaptation collaboration concept adopted in this paper. The used contractual terms as well as monitoring parameters are given in Section 2.2. The algorithmic overview of the different policies used in the analysis is illustrated in Section 2.3. In Section 3, we present the setup configuration of the analysis and give the results. Related work and conclusions are given in Sections 4 and 5 respectively.

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[1] `https://www.eon.de/de/eonde/pk/home/index.htm`

2. Study methodology

2.1. Architectural overview

As mentioned in Section 1, the concept of power adaptation collaboration was investigated in [3]. It takes one step further from previously proposed approaches by taking into account Energy Provider (EP) – Data Centre (DC) as well as Data Centre – IT Customer (ITC) sub-ecosystems. To this end, as Figure 1 depicts, a three-tier architecture has been considered: *Level I, II* and *III.* More precisely, the Level I (*Connection*) contains all the specificities of the involved infrastructure of EPs and DCs. Consequently, the monitoring as well as control of the infrastructure are performed by the Connection level. The Level II (*Negotiation*) corresponds to the decision-making logic implemented in the form of agents to enable power adaptation collaboration. Thus this level needs to interact with Level I, in order to read the current status (e.g. shortage situation) and enact certain power adaptation requests to the involved infrastructure, as well as with Level III which includes the contracts to foster power adaptation collaboration between EP – DC – ITC. Therefore, three different types of contract have been developed in [3]:

1. **GreenSLA** (Green Service Level Agreements) contracts are agreements between DCs and ITCs, which reflect the agreed scope for the data centre to operate in an energy-aware manner and at the same time guarantee a certain level of quality of services (QoS) for the IT customers.
2. **GreenSDA** (Green Supply Demand Agreements) contracts are agreements between EPs and DCs, which define the flexibilities and energy-related contractual terms that these parties grant each other.
3. **GreenWSOA** (Workload Services Outsourcing Agreements) contracts are agreements among federated data centres that set rules for the geographical shifting of workload.

It is worthwhile to mention that the proposed DR approach of [3] is used to preserve the stability of the power grid by either applying it in normal operational state (i.e. to reduce energy costs) or at most during mission-critical state in order to bring the grid back to its normal operational state. Further details on the architectural overview of the proposed approach can be found in [3]. Next, we introduce the contractual terms of the GreenSDA which will be the basis of our analysis for the rest of this paper.

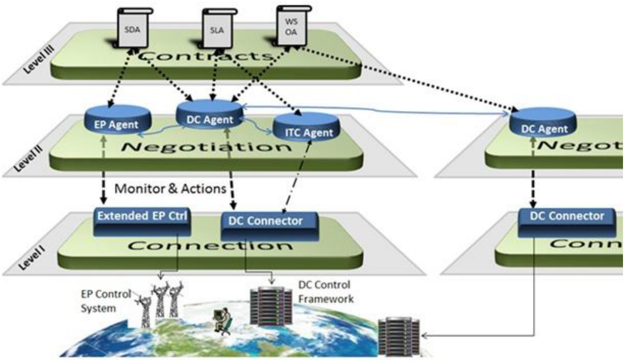


Figure 1: Architectural overview of [3]

2.2. Green agreement

We first begin in Section 2.2.1 by mentioning the contractual terms of [4]. Then in Section 2.2.2, we give the monitoring parameters as well as the metrics necessary for our analysis.

2.2.1. Contractual terms

In [4], a novel agreement called Green Supply Demand Agreement (GreenSDA) to be signed between EP and DCs for power adaptation collaboration was proposed. For our analysis in this paper, we adopt the following proposed contractual terms:

Contractual Term 1. *minDecrease*

Sub Term 1.1. *minDuration*

Sub Term 1.2. *maxDuration*

Contractual Term 2. *maxDecrease*

Sub Term 2.1. *minDuration*

Sub Term 2.2. *maxDuration*

Contractual Term 3. *maxReactionTime*

Contractual Term 4. *maxRejectsPerMonth*

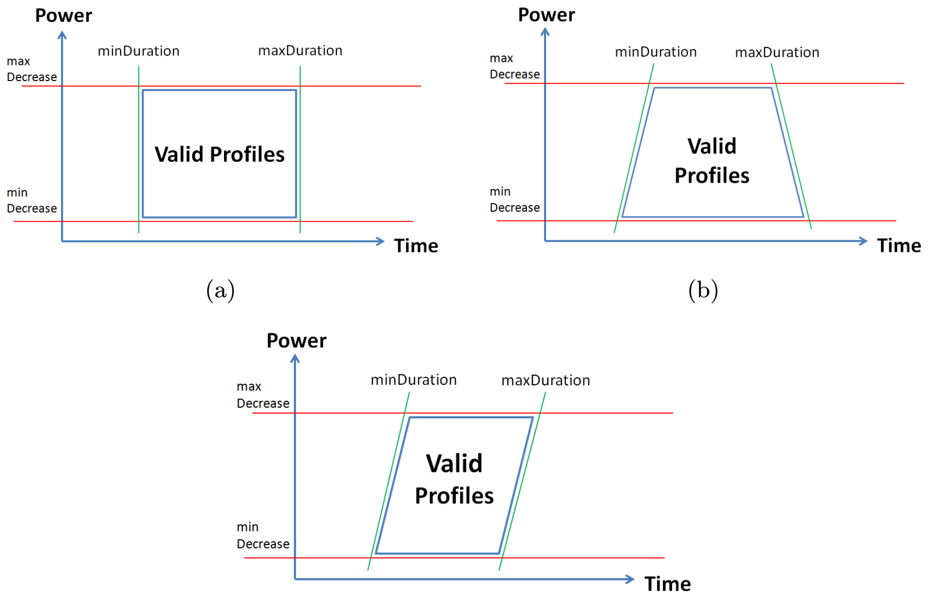
Contractual Term 5. *maxRejectsInSuccession*

Contractual Term 6. *maxRequestsPerMonth*

Contractual Term 7. *requestInterval*

Contractual Term 8. *minEnactionTime*

The Contractual Terms 1 and 2 correspond respectively to minimum and maximum power reduction expressed in kW. For each of the above



(a) (b)

(c)

Figure 2: Borders of DC power adaptation flexibility defined by Contractual Terms 1 and 2

mentioned terms, two sub-terms are defined that specify the minimum and maximum duration (in minutes) of the corresponding power adaptation. Figure 2 illustrates the flexibility borders that can be defined for the case of power decrease when considering Contractual Terms 1 and 2. Note that these flexibility borders define all the valid profiles sent by a DC to EP. Furthermore, the more flat the border is (e.g. Figure 2(a)), the better is for power adaptation collaboration in terms of providing different power adaptation profile possibilities to EP.

The Contractual Term 3 represents the maximum amount of time (in minutes) DC needs to send back a reply to EP. Typically, such a term should have a value of at most 5 minutes. The Contractual Term 4 specifies the maximum number of rejections of DC to EP's power adaptation requests on a monthly basis. The Contractual Term 5 defines the maximum number of successive rejections allowed by DCs. The Contractual Term 6 states the maximum number of requests EP can send to DC on a monthly basis. Since recovering from a power adaptation needs to be performed within a reasonable amount of time, the Contractual Term 7 specifies the minimum period of time (in minutes) between two successive EP's power adaptation requests to DC. The Contractual Term 8 guarantees that the DC has enough time (in minutes) to receive a notice from EP regarding a potential power adaptation request. Note that every time one of the parties breaches one or more contractual terms of GreenSDA, a penalty is applied. Also, incentives are created based on the signed terms. For detailed definition of reward and penalty schemes, interested readers can refer to [4].

2.2.2. Monitoring parameters

The Contractual Terms 4 – 7 need to be monitored in order to keep track of their actual execution by both EP and DCs. To this end, the following *monitoring parameters* were proposed by [4] and adopted in this paper:

1. currentRejectsPerMonth
2. currentRejectsInSuccession
3. currentRequestsPerMonth
4. lastAdaptationStartTime

The first three parameters keep track of the actual number of rejections of DC to EP's requests, the actual number of successive rejections, and the actual number of power adaptation requests sent by EP to DC respectively. The fourth parameter denotes the last power adaptation request's start time of DC. Note that *at the beginning of every month*, those monitoring parameters (except for currentRejectsInSuccession) need to be reset to zero.

Finally, based on the aforementioned contractual terms and monitoring parameters, for the rest of this paper we define the following two metrics:

$$Reject_{Load} = \frac{currentRejectsPerMonth}{maxRejectsPerMonth} \tag{1}$$

$$Request_{Load} = \frac{currentRequestsPerMonth}{maxRequestsPerMonth} \tag{2}$$

2.3. Power profile selecting policies

In this section, we first illustrate the exchanged information concerning power adaptation request and reply. Then in Section 2.3.2, we give a generic algorithmic overview for DC power profile selecting procedure. Finally, in Section 2.3.3, we introduce the considered policies which will be the basis for the analysis of the conducted observations.

2.3.1. Power adaptation process

In short, whenever there is a power shortage situation detected by EP, it sends to all DCs, that are participating in the corresponding DR program, the following information:

1. The adaptation start time denoted by *adaptationStartTime*.
2. The adaptation duration (in minutes) denoted by *adaptationDuration*.

Every DC upon receiving such a request from EP, sends back either NACK or at least one power adaptation profile. The former case denotes that the DC is refusing to collaborate whereas in the latter case, based on its local power adaptation flexibilities (e.g. running DC on UPS or own diesel generator, shifting/shedding workload to reduce power consumption, heating up/cooling down the DC, etc.), the DC sends back to EP one or more power profiles which consist of the following information:

1. The amount of power (in kW) that can be adapted.
2. The amount of time (in minutes) the power can be adapted.
3. The start time of the adaptation.
4. The recovery power (in kW) of the adaptation.
5. The duration (in minutes) for the recovery.

After receiving all the power profiles of DCs, EP needs to apply a *selecting policy* in order to select profiles of different DCs appropriately to fulfil its needs in terms of shortages and surplus[2].

2.3.2. Algorithmic overview

The analysis of the different data centre power profile selecting policies is carried out by executing Algorithm 1. It requires as input the list L of data centres participating in DR program of [7]. The algorithm starts with a loop (line 1) of the participating data centre $dc \in L$ checking its corresponding contractual terms as well as monitoring parameters of GreenSDA (see Sections 2.2.1 and 2.2.2). More precisely, the first “if” clause (line 2) ensures that the EP is not maliciously abusing the DR approach. This is guaranteed by checking the limits of maximum permitted requests per month, the allowable interval between two successive requests that can be sent to DC, as well as the acceptable notice for potential power adaptation request. In that case, the “else” clause (line 14) ensures that a penalty is applied

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[2] Out of the scope of this paper

whenever the EP intentionally sends power adaptation requests more than the maximum agreed Contractual terms 6 – 8. After successful checking of the terms and parameters, the EP sends (line 3) to the corresponding DC a power adaptation request (see Section 2.3.1). The DC upon receiving such a request, sends back either a NACK or a list of adaptation profiles P (line 4).

After receiving the reply from DC, a loop (line 5) of the sent adaptation profile $ap \in P$ checks the other contractual terms as well as monitoring parameters of GreenSDA. To this end, the second “if” clause (line 6) verifies whether the DC is deliberately abusing the DR approach. Among the several conditions tested, “NACK” refers to the fact that DC is not willing to collaborate with the corresponding power adaptation request. The check “Not valid profile” denotes that the corresponding profile sent by DC does not comply with the agreed GreenSDA flexibility borders (see Figure 2). In all those cases, a penalty is applied by incrementing the *currentRejectsPerMonth* monitoring counter (line 7), as well as the *currentRejectsInSuccession* (line 8) by one. Furthermore, this parameter is reset to zero every time that

Algorithm 1 Generic data centre power profile selecting process

```
Require: $L$: List of all DCs with their corresponding GreenSDA that can collaborate with the EP
Ensure: $L'$: List of tuple ($dc$,$P'$) where $dc$ is the unique data centre ID as a key and $P'$ is the list of valid adaptation profile $ap$
 1: for $dc \in L$ do
 2:   if (currentRequestsPerMonth $\leq$ maxRequestsPerMonth $\land$ (adaptationStartTime − lastAdaptationStartTime $\geq$ requestInterval) $\land$ (adaptationStartTime − currentTime $\geq$ minEnactionTime)) then
 3:     Send an adaptation request (e.g. decrease) to $dc$ by specifying the start time (e.g. at 4:15 PM) and duration (e.g. 15 minutes)
 4:     Each $dc$ upon receiving such a request sends back either the possible adaptation profiles $P$ or NACK
 5:     for $ap \in P$ do
 6:       if (NACK || EMPTY || (currentTime − adaptationRequestSentTime $\geq$ maxReactionTime) || Not valid profile || Profile $ap$ start time does not match currentAdaptationStartTime) then
 7:         currentRejectsPerMonth $\leftarrow$ currentRejectsPerMonth + 1
 8:         currentRejectsInSuccession $\leftarrow$ currentRejectsInSuccession + 1
 9:       else
10:         currentRejectsInSuccession $\leftarrow$ 0
11:         Add $ap$ to $P'$
12:       end if
13:     end for
14:   else
15:     Apply penalty to EP
16:   end if
17:   Add ($dc$,$P'$) to $L'$
18: end for
19: Policy($L'$)
```

the data centre sends a valid profile (line 10) and the corresponding adaptation profile *ap* is added to the list of valid power profiles P' (line 11). After checking all the DCs and the validity of their sent replies, the unique data centre ID *dc* as a key as well as the list of valid power profiles P' are added to L' (line 17). Finally, the corresponding DC selecting policy (line 18) is implemented by providing as input the list L' of tuple (dc,P').

Algorithm 2 Fair power profile selecting policy

```
Require: $L'$: List of tuple ($dc$,$P'$) where $dc$ is the unique data centre ID as a key and $P'$ is the list of valid adaptation profile $ap$
for $(dc, P') \in L'$ do
    Sort $L'$ in ascending order of $Request_{Load}$ of data centre $dc$
end for
GoFirst($L'$)
while ((shortage not covered) $\wedge$ !$IsEnd(L')$) do
    Pick the tuple $(dc, P')$
    for all $ap \in P'$ do
        Pick an adaptation profile $ap$ providing the highest power as well as the highest duration
    end for
    currentRequestsPerMonth $\leftarrow$ currentRequestsPerMonth + 1
    GoNext($L'$)
end while
```

2.3.3. Considered policies

As mentioned previously, a DC power profile selecting policy *defines the strategy to pick* among the set of valid profiles L', the relevant ones. Next, we introduce three policies considered in our analysis. The first one was presented by [4], whereas the last two are proposed in this paper.

Fair. The *Fair Policy* (FP) illustrated in Algorithm 2 was first proposed by [4] whose main strategy is to *cover the shortage* as much as possible as well as to *distribute evenly* the burden of power adaptation collaboration among the participating data centres. Thus, such a policy is based on the following two criteria:

1. Sort the tuple $(dc, P') \in L'$ in ascending order of DCs' $Request_{Load}$.
2. Pick an adaptation profile $ap \in P'$ of each data centre dc that provides the highest power and the same (or higher) duration as *adaptationDuration.*

Note that an example of how the adaptation profiles of different data centres are selected using this policy is given in [4].

Cost-saving. One of our policy is called *Cost-saving* (CSP) whose main strategy is to *cover the shortage* as much as possible as well as to *minimise the cost of energy provider* in paying for data centres as incentives for every adapted kWh. Thus, such a policy (see Algorithm 3) is based on the

Algorithm 3 Cost-saving power profile selecting policy

```
Require: $L'$: List of tuple $(dc,P')$ where $dc$ is the unique data centre ID as
    a key and $P'$ is the list of valid adaptation profile $ap$
 1: for $(dc, P') \in L'$ do
 2:   Sort $P'$ in descending order of the adapted power
 3:   Pick the adaptation profile $ap \in P'$ having the highest adapted power
 4:   if $ct_{dc} \notin P_r$ then
 5:     Add the tuple $(dc, ap)$ to the list $L''$ such that $dc$ is the unique data
        centre ID as a key and $ap$ is its adaptation profile with the highest
        adapted power
 6:     Add the tuple $(ct_{dc}, L'')$ to $P_r$ such that $ct_{dc}$ is the cost per shifted
        kWh as a key and $L''$ is the list of tuples $(dc, ap)$ presenting profiles
        of data centres having the same cost per shifted kWh
 7:   else
 8:     Add $(dc, ap)$ to the list $L''$ having the key $ct_{dc} \in P_r$
 9:   end if
10: end for
11: Sort $P_r$ in ascending order of cost per shifted kWh
12: GoFirst($P_r$)
13: $Adapted_{energy} \leftarrow 0$
14: while ((shortage not covered) $\wedge$ $!IsEnd(P_r)$) do
15:   Pick the tuple $(ct, L'')$
16:   for $(dc, ap) \in L''$ do
17:     Pick an adaptation profile $ap$ providing the highest power as well
        as the highest duration
18:     $Adapted_{energy} \leftarrow Adapted_{energy} + Power(ap) * Duration(ap)$
19:     currentRequestsPerMonth $\leftarrow$ currentRequestsPerMonth + 1
20:     if $Adapted_{energy} \geq Requested_{energy}$ then
21:       Exit: Shortage covered
22:     end if
23:   end for
24:   GoNext($P_r$)
25: end while
```

following criteria:

1. Order the set of profiles of each data centre in descending order of the adapted power (line 2).
2. Pick from each data centre, the profile *ap* that provides the highest adapted power (line 3).

Algorithm 4 Peak-avoidance power adaptation profile selecting policy

```
Require: $L'$: List of tuple ($dc$,$P'$) where $dc$ is the unique data centre ID as
    a key and $P'$ is the list of valid adaptation profile $ap$
for $(dc, P') \in L'$ do
    Sort $P'$ in descending order of the adapted power
    Pick the adaptation profile $ap \in P'$ having the highest adapted power
    Add the tuple $(dc, ap)$ to the list $L''$ such that $dc$ is the unique data
        centre ID as a key and $ap$ is its adaptation profile with the highest
        adapted power
end for
Sort $L''$ in ascending order of recovery energy each adaptation profile $ap$
    needs
GoFirst($L''$)
$Adapted_{energy} \leftarrow 0$
while ((shortage not covered) $\wedge$ !$IsEnd(L'')$) do
    Pick the tuple $(dc, ap)$
    Pick the adaptation profile $ap$ providing the highest power as well as
        the highest duration
    $Adapted_{energy} \leftarrow Adapted_{energy} + Power(ap) * Duration(ap)$
    currentRequestsPerMonth $\leftarrow$ currentRequestsPerMonth + 1
    if $Adapted_{energy} \geq Requested_{energy}$ then
        Exit: Shortage covered
    end if
    GoNext($L''$)
end while
```

3. Add the selected profile *ap* of each data centre to the same level (entry) having the same cost per adapted kWh (lines 4–8).
4. Sort the adaptation profiles of different data centres in ascending order of the cost (line 11).
5. Pick, as long as the shortage is not covered, the adaptation profile of different data centres that have the least cost (lines 14–24).

Peak-avoidance. The second policy that we propose in this paper is called *Peak-avoidance* (PAP). Such a policy has the main strategy of *covering the shortage* as much as possible as well as *preserving the stability of the power grid* by circumventing power peaks that might arise during the recovery phase after a successful power adaptation. Thus, such a policy (see Algorithm 4) is based on the following criteria:

1. Order the set of profiles of each data centre in descending order of the adapted power (line 2).
2. Pick from each data centre, the profile *ap* that provides the highest adapted power (line 3).
3. Add the previously selected profile *ap* of different data centres to the list of adaptation profiles L'' (line 4).
4. Sort L'' in ascending order of the recovery energy each adaptation profile *ap* needs (line 6).
5. Pick, as long as the shortage is not covered, the adaptation profile of different data centres that have the least recovery energy (lines 9–17).

3. Evaluation and obtained results

3.1. Configuration and setup

The observations were conducted by studying the power grid's status of a German energy provider E-on. To this end, we obtained the average power consumption of the grid computed for every 15-minute interval (e.g. 4 values per hour) for the year 2011. Furthermore, we identified the maximum average power consumption of the grid for the year and defined as a shortage situation every 15-minute interval where the difference between maximum average power and the corresponding average power of the interval is less than or equal to 5% of this maximum average power. Consequently, we identified *19 power shortage situations* for our analysis. For this purpose, we configured a discrete event simulation consisting of 15k data centres having three different sizes in terms of maximum adapted power:

1. Small data centre: It has a maximum adapted power capability of 105 kW.
2. Medium data centre: It has a maximum adapted power capability of 550 kW.
3. Large data centre: It has a maximum adapted power capability of 5700 kW.

In order to cover a broad range of possibilities, we set up three different levels of data centre collaboration:

1. High collaboration: Each data centre sends back to energy provider one *small*, *medium* and *large* power adaptation profiles.
2. Medium collaboration: Each data centre sends back one *small* and 50% of the time one *medium* and *large* power adaptation profiles.

3. Low collaboration: Each data centre sends back one *small* power adaptation profile with a probability of 50% to send a NACK, and 25% of the time one *medium* and *large* power adaptation profiles, with a probability of 12.5% to send a NACK for each of the two profiles. Note that, at this level of collaboration, there is a probability of 50% to reject a power adaptation collaboration.

It is worth pointing out that the collaboration level indicates the extend to which the data centre is willing to cooperate with the energy provider for power adaptation purposes. Regarding the power adaptation profile sizes, the following criteria is used to define them accordingly:

1. Small profile: It is defined by setting the value of the *power* to the contractual term *minDecrease* and its *duration* to the sub term *maxDuration* (i.e. Contractual Term 1 and Sub Term 1.2) specified in GreenSDA. Also, such a profile needs no recovery power.
2. Medium profile: It is defined by setting the value of the *power* to the mean of the contractual terms *minDecrease* and *maxDecrease* (i.e. Contractual Term 1 and 2) of GreenSDA. The *duration* is set to the mean value of the Sub Terms 1.2 and 2.2 (i.e. *maxDuration*) as specified in GreenSDA. The recovery energy (i.e. power and duration) is set to be slightly higher than the adapted energy of the profile.
3. Large profile: This profile is defined by setting the value of the *power* to the the contractual term *maxDecrease* and its *duration* to the sub term *maxDuration* (i.e. Contractual Term 2 and Sub Term 2.2) specified in GreenSDA. The recovery energy (i.e. power and duration) is set to be slightly higher than the adapted energy of the profile.

3.2. Considered contractual terms

The GreenSDA's contractual terms are specified in XML format where values for such terms are chosen randomly within the range of lower and upper bounds defined by the size of the corresponding data centre. More precisely, for large, medium and small data centres, the Contractual Term 1 (*minDecrease*) is specified by taking an arbitrary factor between 5% and 15% of 5700 kW, 550 kW and 105 kW respectively. Furthermore, values for the other two sub terms are chosen arbitrarily in the following manner:

1. *minDuration*: Between 10 and 120 minutes.
2. *maxDuration*: Between 120 and 600 minutes.

For large, medium and small data centres, the Contractual Term 2 (*maxDecrease*) is defined by taking an arbitrary factor between 15% and 66% of

5700 kW, 550 kW and 105 kW respectively. Furthermore, values for the other two sub terms are chosen arbitrarily in the following manner:

1. *minDuration*: Between 5 and 15 minutes.
2. *maxDuration*: Between 15 and 120 minutes.

With respect to the remaining contractual terms, the values are chosen arbitrarily in the following manner:

1. Contractual Term 3 (*maxReactionTime*) between 1 and 5 minutes.
2. Contractual Term 4 (*maxRejectsPerMonth*) between 1 and 2.
3. Contractual Term 5 (*maxRejectsInSuccession*) between 1 and 2.
4. Contractual Term 6 (*maxRequestsPerMonth*) between 1 and 4.
5. Contractual Term 7 (*requestInterval*) between 180 and 240 minutes.
6. Contractual Term 8 (*minEnactionTime*) to 600 minutes.

3.3. Simulation-relevant parameters

As mentioned previously, our analysis is carried out by considering 15k data centres participating in the DR program of [7]. In order to cover a wide spectrum of possible observations, in this paper we consider the following five different scenarios:

1. Scenario 1: 77% small, 21% medium and 2% large data centres providing in total a maximum adaptation power of 4850115 kW.
2. Scenario 2: 50% small, 35% medium and 15% large data centres providing in total a maximum adaptation power of 16500000 kW.
3. Scenario 3: 73% small, 10% medium and 17% large data centres providing in total a maximum adaptation power of 16499960 kW.
4. Scenario 4: 33.3% small, 33.3% medium and 33.3% large data centres providing in total a maximum adaptation power of 31775000 kW.
5. Scenario 5: 2% small, 21% medium and 77% large data centres providing in total a maximum adaptation power of 67599000 kW.

Each of the above mentioned five scenarios is analysed by taking into account the three different collaboration levels (e.g. high, medium, low) of data centres as well as the three different data centre power profile selecting policies of Section 2.3.3. This results in conducting *9 numerous observations each being tested 100 times.* To derive results with statistical correctness, we choose a confidence interval of 95%.

In the rest of this section, we compare the five scenarios and their corresponding observations by taking into account the following metrics:

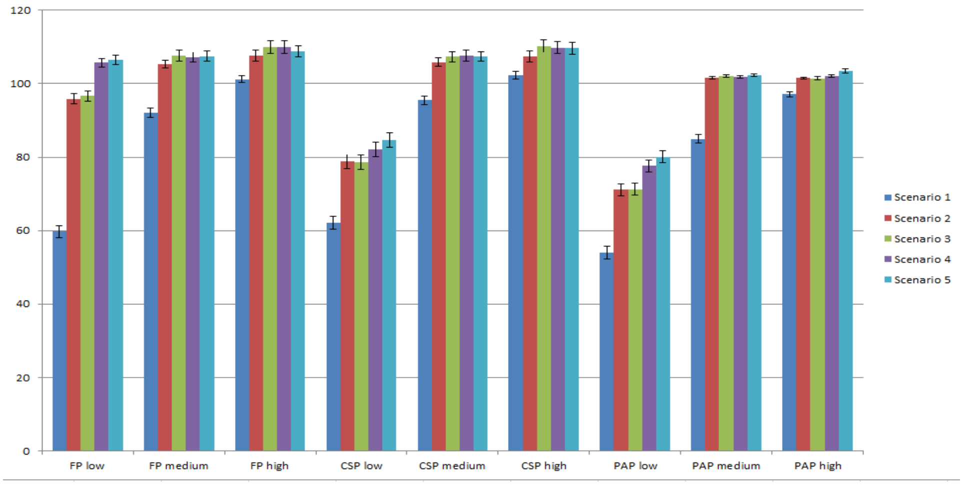


Figure 3: Shortage coverage of the five scenarios

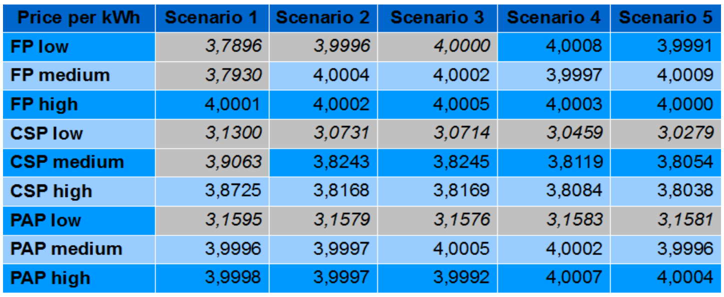
1. Covered shortage: It indicates the extend to which a given shortage situation is covered by means of the power adaptation collaboration with data centres.
2. Price per shifted kWh: It indicates the amount of monetary incentive the energy provider needs to pay to the data centre for every shifted kWh.
3. Request load: It indicates the distribution of the power adaptation requests among the participating data centres (see Equation 2).
4. Reject load: It indicates the distribution of the power adaptation rejects of the participating data centres (see Equation 1).
5. Recovery energy: It indicates the amount of recovery energy the corresponding power adaptation collaboration requires.

3.4. Obtained results

In this section, we present the results obtained by the analysis performed in this paper.

3.4.1. Covered shortage

Figure 3 illustrates the percentage of the covered shortage for the five different scenarios. The X-axis denotes the nine different observations (low, medium and high collaboration with respect to fair (FP), cost-saving (CSP) and peak-avoidance (PAP) policies) of each scenario whereas the Y-axis presents the percent of the covered shortage. Among the different scenarios,



Price per kWh	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
FP low	*3,7896*	*3,9996*	*4,0000*	4,0008	3,9991
FP medium	*3,7930*	4,0004	4,0002	3,9997	4,0009
FP high	4,0001	4,0002	4,0005	4,0003	4,0000
CSP low	*3,1300*	*3,0731*	*3,0714*	*3,0459*	*3,0279*
CSP medium	*3,9063*	3,8243	3,8245	3,8119	3,8054
CSP high	3,8725	3,8168	3,8169	3,8084	3,8038
PAP low	*3,1595*	*3,1579*	*3,1576*	*3,1583*	*3,1581*
PAP medium	3,9996	3,9997	4,0005	4,0002	3,9996
PAP high	3,9998	3,9997	3,9992	4,0007	4,0004

Figure 4: Price per shifted kWh

except for Scenarios 4 and 5 of FP-low, we notice that all the five scenarios can not achieve full coverage for the case of low collaboration. Also, Scenario 1 has in all cases weaker coverage than the other four scenarios due to the low maximum overall power adaptation of 4850115 kW (see Section 3.3). For all levels of collaboration and scenarios, the PAP has weaker coverage than the FP and CSP. This is due to the fact that PAP uses small profiles as long as they are available since such type of profiles do not require recovery power. Consequently, more replies are needed to cover the same amount of shortage, thus exhausting the DC's maximum amount of agreed power adaptation requests per month quickly. This leads us to the conclusion that FP and CSP have the edge over PAP when power shortage coverage is concerned as long as the DCs have small agreed number of requests per month (i.e. *maxRequestsPerMonth*) that is the case in this analysis which is set to a value between 1 and 4 (See Section 3.2).

3.4.2. Price per shifted kWh

For our analysis, the energy provider pays between 3.8 ct and 4.2 ct back to the data centre as an incentive for every shifted kWh. Figure 4 demonstrates the price per shifted kWh of the different scenarios and their corresponding observations. The greyed out values of the figure are not interesting for our evaluation. This is because every time that a shortage situation is covered by 0%, the simulation computes a price of 0 ct/kWh. When computing the average over all shortage situations, these zero prices lower the outcome. Note that such a situation happens at low collaboration level due to sending back a NACK. Consequently, all results where this happened were discarded. The remaining numbers show that FP and PAP perform around 4.0 ct/kWh because both policies neglect the price when choosing power adaptation profiles. Since the incentive is uniformly distributed among all valid power adaptation profiles, both policies perform at

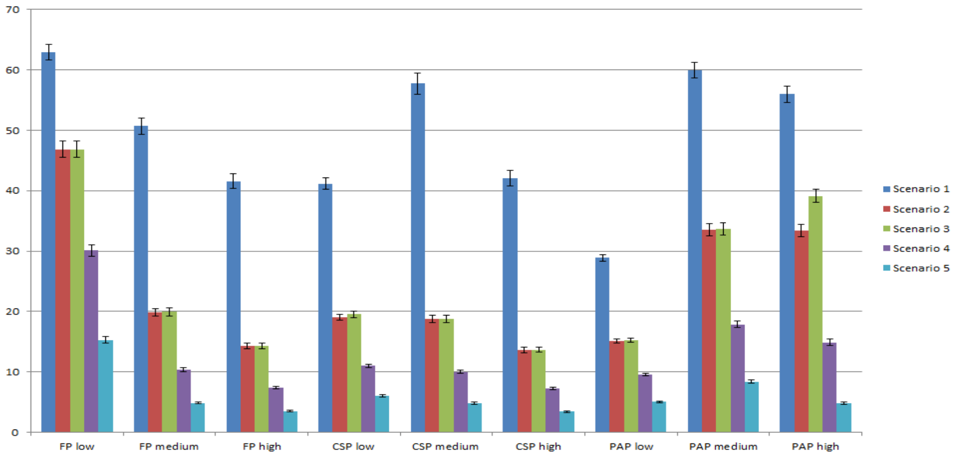


Figure 5: Ratio of current request to maximum requests per month

the average of the possible incentives which is 4.0 ct. CSP performs near optimum which is 3.8 ct as the lowest possible incentive.

3.4.3. Request load

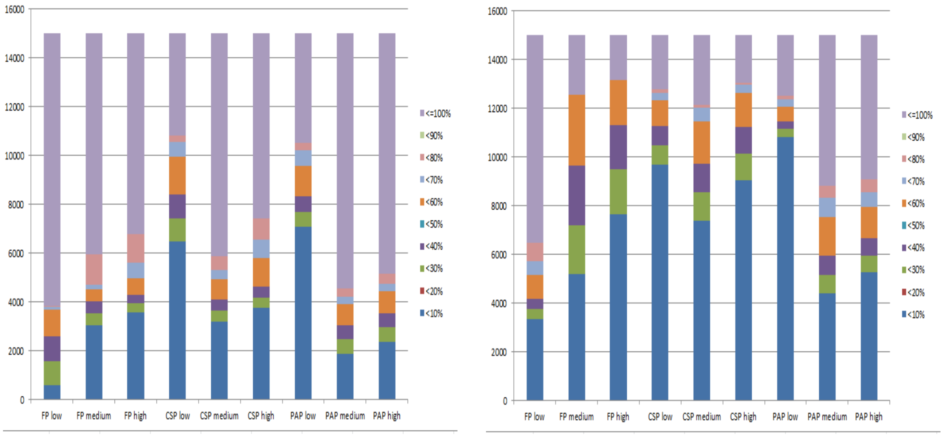
Figure 5 presents the overall ratio of current requests to maximum requests of the five scenarios. The X-axis denotes the nine different observations (low, medium and high collaboration with respect to fair (FP), cost-saving (CSP) and peak-avoidance (PAP) policies) of each scenario, whereas the Y-axis shows the overall request load in percent computed using Equation 2. The lower this ratio is, the better is the corresponding result. Among the five scenarios, Scenario 1 has the worst ratio whereas Scenario 5 has the best one. This is due to the fact that for the former case, most of the data centres are of small size. Consequently, more data centres are needed to cover a given power shortage situation, leading to raising the number of power adaptation requests. Hence, we notice that the ratio gets better gradually as the number of large data centres increases from Scenario 1–5. Furthermore, at low level of collaboration, FP has worse ratio than CSP and PAP. This is because fair policy tries to distribute evenly the requests among the data centres. As a matter of fact, at low collaboration level (i.e. 50% of NACK), the fair policy exhausts maximum requests per month of each data centre. Also, PAP has the worse ratio than the other two at medium and high level of collaboration. Figure 6 further demonstrates the distribution of power request load among 15k data centres of the numerous scenarios. The different colours denote the request load ratios (e.g. 10%–100%). In conclusion, despite the fact that at low collaboration level FP has the worse ratio, however in all other cases FP has the edge over the other two policies.

3.4.4. Reject load

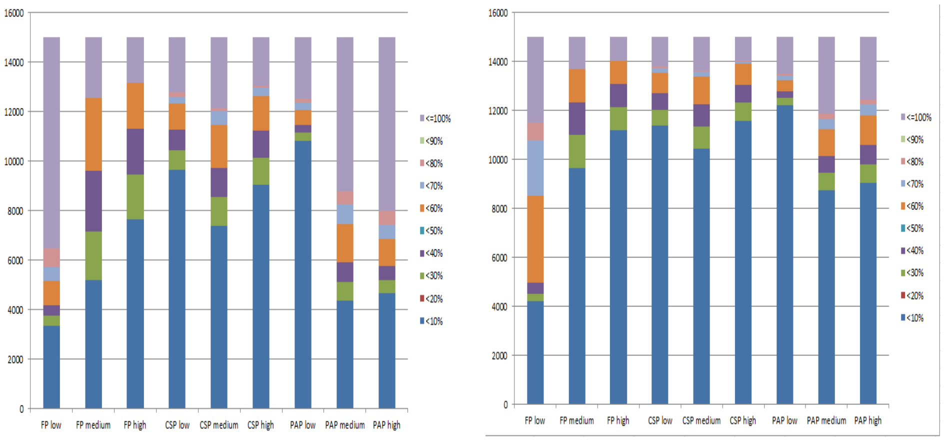
In order to have a fruitful analysis, we studied the reject load of the different scenarios for the case of low collaboration. This is due to the fact that at such a level of collaboration, there is a probability of 50% for data centres to send back a NACK (i.e. rejection). Figure 7 presents the overall ratio of current rejects to maximum rejects of the five scenarios. The X-axis denotes the three different policies (i.e. fair (FP), cost-saving (CSP) and peak-avoidance (PAP)) of each scenario for the case of low collaboration level, whereas the Y-axis shows the reject load in percent computed using Equation 1. The lower this ratio is, the better is the corresponding result. We notice from the figure that all the scenarios have at least 50% of rejection rate. Furthermore, among the five scenarios, Scenario 1 has the best ratio whereas Scenario 5 has the worst one. The behaviour alters with the scenarios due to the fact that smaller average reply leads to quick exhausting of the permitted rejections per month. Therefore DCs have less chance to send rejects for small scenario numbers (maximum adaptation power rises with the scenario number which leads average reply to get bigger). Consequently, exhausted DCs are not asked anymore for adaptation causing the reject rate to become lower. Furthermore, by comparing Scenarios 2 and 3, we notice that both scenarios, having equal maximum adaptation power and therefore equal average reply size (power and energy), cause similar reject load. Also, except for Scenario 1 which can not achieve full coverage with any policy because DCs are exhausted early, the CSP and PAP have better reject rate than FP. The bad performance of FP can be explained by its higher coverage ratio. Coverage below 100% means that most DCs are exhausted.

3.4.5. Recovery energy

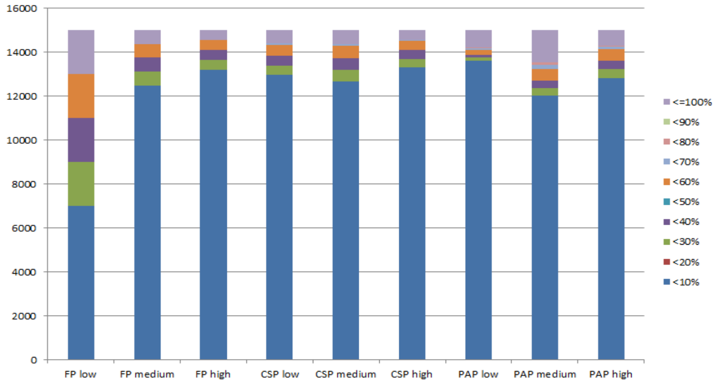
Every time that a data centre finishes a power adaptation collaboration, it immediately starts its recovery process, where in *most cases* such a phase requires energy to recover from the carried out adaptation. For instance, when a data centre runs its IT equipment on UPS during the adaptation phase, it needs to recharge the used battery of the UPS during the recovery phase. The only case where an adaptation does not require a recovery energy is when the data centre degrades the QoS of the provided services. As mentioned previously, we assume in this paper that small power adaptation profiles have no recovery energy. For this purpose, in Figure 8 we present



(a) Scenario 1 (b) Scenario 2



(c) Scenario 3 (d) Scenario 4



(e) Scenario 5

Figure 6: Request load distribution of data centres for the different scenarios

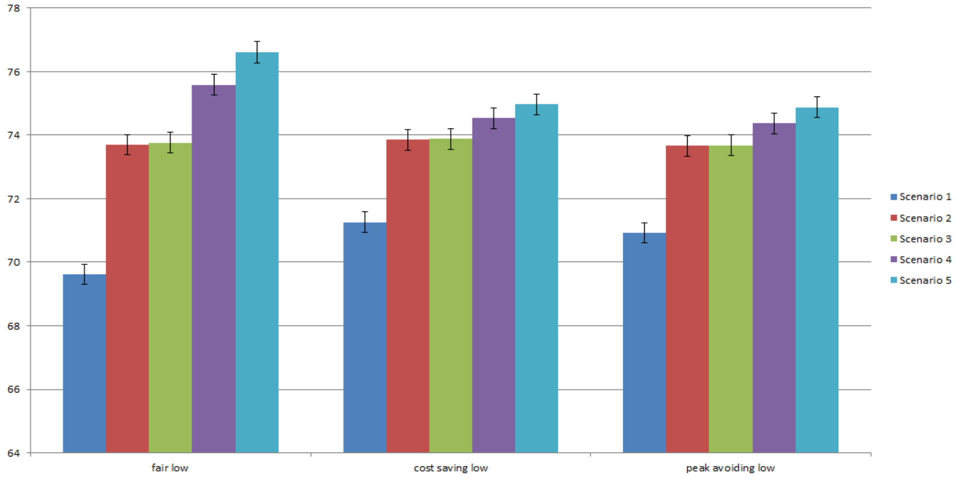


Figure 7: Ratio of current reject to maximum rejects per month

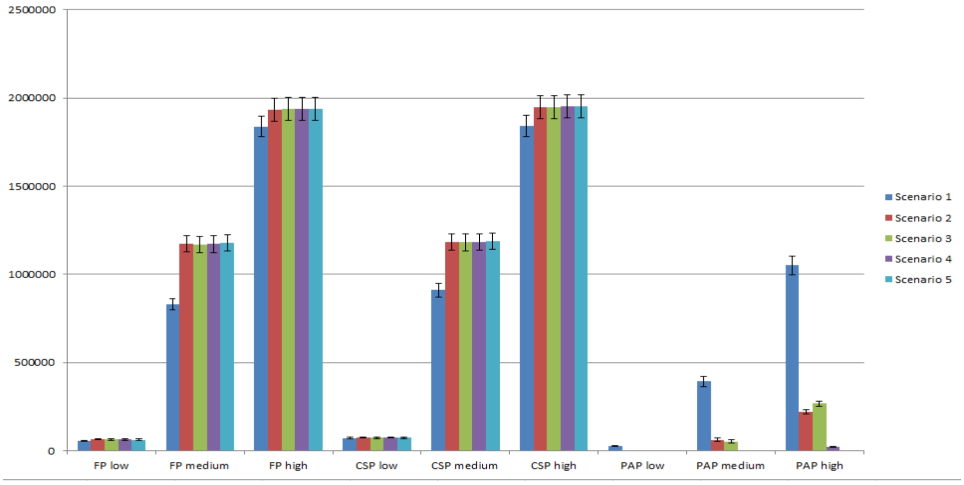


Figure 8: Required energy needed to recover from the carried out adaptation

the different scenarios of our analysis with respect to the required recovery energy. The X-axis denotes the nine different observations (low, medium and high collaboration with respect to fair (FP), cost-saving (CSP) and peak-avoidance (PAP) policies) of each scenario, whereas the Y-axis shows the required recovery energy in kWh. We notice that at low collaboration level, all the observations have a low recovery energy. This is because during such collaboration level, the data centres send small power adaptation profiles which require no recovery energy as mentioned above. Furthermore, both CSP and FP have quite similar required recovery energy whereas we notice the big improvements for the case of PAP in terms of low required recovery energy. This is due to the fact that peak-avoidance policy picks power adaptation profiles with minimum required recovery energy. Also, for the case of PAP, we observe that the results get better (i.e. lower required energy) gradually from Scenario 1–5.

4. Related work

As mentioned in this paper, the Green Supply Demand Agreement between EP and DCs is a novel and recent concept introduced within the context of [7] for Demand Response (DR). Consequently, to the best of our knowledge, no new contractual terms have been proposed other than the ones adopted in this paper. Having said that, lately there have been some efforts in studying and analysing the participation of data centres in DR programs. In [8], the authors conducted field tests to improve the understanding of the DR opportunities in data centres. The study evaluated an initial set of control and load migration strategies and economic feasibility. The findings show that with minimal or no impact to data centre operations, a demand savings of 25% at the data centre level or 10% to 12% at the whole building level can be achieved with strategies for cooling and IT equipment, and load migration. Unlike this paper, no further studies were carried out in [8] in order to evaluate the power adaptation collaboration between EP and DCs.

Proprietary DR programs and solutions for commercial, institutional and industrial facilities were proposed in different European countries, such as United Kingdom, Germany, France, Ireland, Austria and Italy. For instance, Entelios [9] offers an automated industrial demand response solution, called *Demand-Response-as-a-Service*. The DR solution of Entelios enables utilities (e.g. energy provider) to set up DR programs, and grid operators to manage decentralised electrical loads, storage, and generation in near real-time. EnerNOC [10] offers a proprietary DR mechanism, called *DemandSmart*, for commercial, institutional and industrial facilities. EnerNOC participates in DR programs in United Kingdom, e.g. National Grid's Short Term Operating Reserves Programme[3], and UK Power Networks' Low Carbon London[4]. EDF Energy [11] offers a proprietary DR solution for business customers called *Smart Response*[5]. Customers are paid for their willingness to react to power adaptation requests as well as for every MW power consumption reduction. Energy Pool [12] provides for energy market stakeholders a proprietary DR management system. The DR solution of Energy Pool is fully automated and supports different DR approaches. The Short Term Active Response [13] (STAR) program of EirGrid[6] has been operating for over 20 years. Participants of *STAR* agree to make their load available for short term interruptions (e.g. 5 minutes duration, 10–20 times per year). In return, the transmission system operator pays for the energy that the customer makes available. An under-frequency relay is used to initiate the interruption. From the aforementioned proposed proprietary solutions, none of them so far have been applied for the case of data centres, due to lack of knowledge and insights. Hence, we consider the analysis carried out in this paper contributes in providing insights for the stakeholders in energy market to set up DR solutions for the case of data centres.

5. Conclusion and next steps

Demand Response (DR) is a set of actions taken by the customers of the power grid to change the electricity load in order either not to jeopardize the grid or to react to sudden peaks of electricity costs. Data centres, due to their prominent energy use and highly automated infrastructure, have been identified as great candidates to participate in DR. To this end, the power adaptation collaboration between energy provider (EP) and data centres (DC) was studied in [7]. A novel supply demand agreement was proposed which defines energy-relevant contractual terms for power adaptation collaboration. In this paper, we adopted those contractual terms for power shortage situation, and analysed them based on three different power profile selecting policies, namely *fair* (FP), *cost-saving* (CSP) and *peak-avoidance*

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[3] `http://www.nationalgrid.com/uk/Electricity/Balancing/services/balanceserv/reserve_serv/stor/`

[4] `http://lowcarbonlondon.ukpowernetworks.co.uk/`

[5] `http://www.edfenergy.com/products-services/large-business/PDF/B2B_ePublications/DEMAND-REPSONSE.pdf`

[6] `http://www.eirgrid.com`

(PAP). For this purpose, we set up a simulation consisting of 15k data centres of varying sizes and collaboration levels (low, medium and high).

The performed evaluation illustrates that each policy has its pros and cons based on the studied circumstances. More precisely, the simulation results show that each policy produced good outcome fulfilling its goal, but scored worse in others. For instance, FP achieves workload scatter, but performs neither cost-effective, nor saving in matters of recovery energy usage. On the other hand, the PAP almost eliminated the need for recovery energy, however it needs more profiles to choose from to reach an equal coverage ratio. Finally, CSP achieves mean results for all the considered parameters but the imminent monetary benefit could encourage electric market stakeholders to participate in a real world application. We believe that these results serve as a guideline and provide further insights to energy market stakeholders in setting up demand response programs for the case of data centres.

As a future work, this work needs to be extended by proposing further other policies having real-life use cases that cover most or even specific interests of different energy market stakeholders. Moreover, the topic of malicious usage of the whole ecosystem of EP-DC needs to be addressed carefully by taking into currently investigated approaches and solutions.

6. Acknowledgment

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7. Vitae

Robert Basmadjian. Has been working as an IT Consultant at ONE LOGIC Gmbh in Passau, Germany. He was also affiliated to University of Passau as a Post Doctorial fellow between 2009 and 2013. He holds an M.Sc. and Ph.D. in Computer Science from the University of Toulouse. His research interests are replication in distributed systems, mathematical modelling of systems, and forecasting algorithms. He participated in the EU funded projects ALL4Green, FIT4Green and EuroNF.

Lukas Müller. In June 2009, he started to prepare his BA degree in Internet Computing at University of Passau. He attended several seminars related to Smart Grid technologies. He has also been involved in software development projects, such as the one for Supply Chain Optimisation of Gemany's major car manufacturer.

Hermann De Meer. Is currently appointed as Full Professor at the University of Passau, Germany, and as Honorary Professor at University College London, UK. He is director of the Institute of IT Security and Security Law (ISL) at the University of Passau. His main research interests include IT security and resilience, virtualization and energy efficiency, complex and self-organizing systems, peer-to-peer systems, quality of service and performance modeling, Internet protocols, home networking, and mobile computing. Hermann de Meer has led several nationally and internationally funded projects on Performance Modeling and Computer Networking. He currently holds several research grants funded by the Deutsche Forschungsgemeinschaft (DFG) and by the EU (FP6 and FP7).

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[11] `http://www.edfenergy.com/`.

[12] `http://www.energy-pool.eu/en/`.

[13] `http://www.eirgrid.com/operations/ancillaryservicesothersystemcharges/demandsidemanagementdsm/shorttermactiveresponsestar/`.