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Extending the envelope of demand response provision through variable speed pumps

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Abstract

Changes in power generation and supply and changes in water distribution systems are creating new opportunities for water utilities to enhance operational efficiency and income through the use of advanced control and optimisation. First, the increase in renewables penetration into the grid is causing a growth in energy storage schemes. Second, variable speed pumps are now fitted to most new systems and many existing water distribution systems are being retrofitted with variable speed pumps to improve the efficiency of the operation. We study how these trends can be jointly exploited to provide energy storage from a water distribution system. We investigate how variable speed drive pumps can enhance the ability of a water distribution network to provide demand response energy to the grid. We show that demand response provision from water distribution systems can be improved through the use of variable speed pumps. We also demonstrate that a network equipped with variable speed pumps can provide demand response profitably across a wider range of operating scenarios compared to a network equipped with only fixed-speed pumps. The results highlight another potential benefit of variable speed pumps in water distribution systems.

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1. Introduction

Water distribution systems (WDS) consume a considerable amount of a cities energy, up to 5% of its total usage [1]. Variable speed drive (VSD) pumps can be used to reduce the energy used to operate a WDS through the increased variation in the performance. Reductions in energy cost of 35% in irrigation systems have been demonstrated through the use of variable speed pumps [2]. These savings have lead to retrofitting of VSD pumps to existing systems and increasingly new systems are being equipped with VSD pumps. On the energy supply side electricity storage schemes and grid management methods are becoming ever more important with the introduction of more decentralised renewable production [3]. The intermittent nature of these sources and the unavailability of contemporary technology for storing large quantities of electrical energy efficiently and cost effectively has led to a demand for new energy storage systems and more intelligent electricity demand management [4]. This work seeks to combine these two trends in the water supply and energy supply systems and to evaluate the mutual benefits that can be generated.

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The demand management scheme investigated here is demand response (DR). In demand response, an electricity consumer reduces or shifts its power consumption when requested to do so in exchange for compensation. An electricity consumer with an electricity demand that is predictable into a future operational horizon, providing DR is achieved by reducing and shifting its electricity consumption compared to the predicted consumption [5]. Different DR mechanisms impose different requirements on how long the power reduction must last, how large it has to be, at what rate it must be reduced and within what time frame it must be achieved. A detailed summary of possible mechanisms and their properties is provided in [6]. It has been shown that considerable GHG emission savings can be achieved through a range of demand response programs [7]. Demand response schemes have also been shown to enable a larger integration of wind power generate [8,9]. Demand response provision from a WDS with fixed pumps was first evaluated in [10]. Here we explore how a network equipped with VSD pumps could participate in a DR scheme and how the finer control of the VSD pump power consumption improves the potential of participation in a demand response scheme.

The optimisation of the pump schedule including the operating condition of the variable speed pump has been approached with a range of meta-heuristics such as ant colony optimisation [11], or genetic algorithms [12]. Other methods minimize the specific energy consumption of the system and solve an idealized WDS approximation evaluating a series of local optima [13]. The main limitation of these approaches lies in their inability to find certifiably optimal schedules. The optimal control of a WDS with VSD pumps can also be found using a mixed integer non-linear programming approach, using third order polynomial approximations for the VSD pump properties [14]. The problem can be reformulated as a mixed integer linear program (MILP), using a piecewise linear approximation. By linking the power consumption to the flow rate and head difference created by the pump the non-linear relations of power, head, flow and pump speed are approximated through a proxy variable. The non-linear equations describing the exact pump state are solved after the optimal schedule has been computed. The pump schedule optimisation method for a network with VSD pumps used here is described in [15,16].

2. Method

2.1. Modelling demand response

In the United Kingdom, National Grid operates the electricity grid maintaining the desirable frequency of 50Hz. To do this National Grid calls frequency reserve providers in case of a significant drop in frequency. This is followed by reserve energy providers to relieve the faster acting and more expensive to operate frequency services. However, frequency response services require sudden and fast switching of equipment, in this case pumps. As VSD pumps have no advantage over a fixed speed pump in such an operating regime, only reserve energy provision is considered here. Furthermore, analysis of DR from WDS showed that STOR services were more suitable as a DR scheme for a WDS to explore first [10].

The reserve energy provision service we consider is the Short Term Operational Reserve (STOR), which is brought on-line within 20-30 minutes [17]. A STOR provider offers a steady demand reduction and must deliver the reduction within 4 hours after being called and may be required to reduce the demand for up to 2 hours. However, the tender records show that the mean call duration in 2013 was 82 minutes and that National Grid prefers services that can respond within 10 – 20 minutes [4]. Since the minimum offered power requirement for STOR participation in the UK is 3MW, only large WDSs would be able to participate in a STOR scheme directly. However, through an aggregator, a company that aggregates several consumers and bids their capacities to National Grid, a smaller WDSs could participate in these mechanisms by sharing the profits generated with the aggregator. To offer STOR National Grid recognises a range of pathways to suit the wide range of suppliers. The pathways modelled here are based on offering STOR services during both availability windows or just in one, this can be achieved through tendering either a committed or flexible service.

Table 1: Summary of the range of monetary rewards for STOR service options [4,18,19].

(Windows available)	Availability (£/MW/h)	Energy pay £/MWh	Total (£/ MW) (R)
1 st & 2 nd	7 – 9	75 – 200	30k – 45k
1 st only	1.8 – 2.5	75 – 200	15k – 30k

2.2. Problem formulation

The optimisation problem for the optimal WDS pump schedule can be formulated as:

$$\begin{aligned} &\text{minimise: Pump operation cost – DR revenue} \\ &\text{subject to: Hydraulic constraints of pumps and pipes,} \\ &\quad \text{mass balance of the system,} \\ &\quad \text{additional constraints from DR provision} \end{aligned} \quad (1)$$

The method is only summarised here briefly [15,16]. To simulate the power consumption of the WDS and maintain the problem as an MILP, a linear approximation of the power consumption of a VSD is used, as the approximation of the power consumption also provides a constraint, which must be linear in a MILP.

The objective function has two elements. The pump operating cost for a variable speed drive (VSD) pump, the energy consumption, i.e. is assumed proportional to the power setting here described by $\mathcal{T}_{i_p,j} \in [0, 1]$. The energy consumption is then given by:

$$f_1(\cdot) := \sum_{i_p=1}^{i_p=N_p} \sum_{j=1}^{j=N} (\mathcal{T}_{i_p,j} c_{\mathcal{T},i_p} + q_{i_p,j} c_{q,i_p}) C_{E,j} \quad (2)$$

where $c_{\mathcal{T},i_p}$ and c_{q,i_p} are linear coefficients for the power consumption approximation of pump i_p and $C_{E,j}$ is a constant term describing the length of time step j and the cost of energy during time step j . The throttle setting of the pump is described by $\mathcal{T}_{i_p}$. The revenue from providing demand response is proportional to the power committed to the scheme. This is represented by:

$$f_2(\cdot) := -P_{dr} \times R \quad (3)$$

where R is the expected revenue per MW committed as summarised in Table 1 and P_{dr} is the power committed to DR given by constraint (4). To be able to provide this power as demand response, the WDS must guarantee that it would always consume this offered power unless it answers a DR call. The power consumed by the pumps at a given time step is given by:

$$\mathcal{T}_{i_p,j} c_{\mathcal{T},i_p} + q_{i_p,j} c_{q,i_p} \geq P_{dr} \quad (4)$$

The head difference across a pump can be modelled by a set of linear constraints describing a convex set approximating the characteristic curve. For a VSD pump i_p connecting nodes $J1$ and $J2$, the constraints at a given time step are:

$$h_{J1} - h_{J2} \leq \begin{cases} m_{i_p,1}^p q_{i_p} + c_{i_p,1}^p \mathcal{T}_{i_p} & \text{and} \\ m_{i_p,2}^p q_{i_p} + c_{i_p,2}^p \mathcal{T}_{i_p} & \text{and} \\ \vdots & \\ m_{i_p,5}^p q_{i_p} + c_{i_p,5}^p \mathcal{T}_{i_p} & \text{if: } T_{i_p} = 1 \\ \Delta h_{ub}, q_{i_p} = 0 & \text{if: } T_{i_p} = 0 \end{cases} \quad (5)$$

where $m_{i_p,1} \dots m_{i_p,5}$ and $c_{i_p,1} \dots c_{i_p,5}$ are the linear coefficients. Δh_{ub} is an upper bound on the pressure head generated by the pump. $T_{i_p,j} \in \{0, 1\}$ is a binary constraint to define the ON-OFF state of the pump. Only a pump that is ON can it have non-zero throttle. This is enforced through a constraint of the form:

$$\mathcal{T}_{i_p,j} \leq T_{i_p,j} \quad (6)$$

Tanks provide storage capacity in the networks providing water supply when the supply from the pumps is less than the demand. For a tank J with flows q_{in} and q_{out} the mass balance for time steps $j = 1 \dots N - 1$ is given by:

$$q_{in,j} + q_{out,j} = (h_{J,j+1} - h_{J,j}) \times A_J, \quad (7)$$

where the surface area of the tank is given by A_J . When providing demand response, the WDS must be able to satisfy the expected water demand from consumers for the maximum possible duration of the DR event. This is enforced in the optimization model by specifying a minimum fill level for tanks, which depends on the maximum DR time

offered. This increases the lower bound in the tank dependent on the demand level by:

$$h_{\min_{DR} J,i} = h_{\min_{norm} J,i} + \frac{V_d J,i}{A_J} \quad (8)$$

Since demand patterns are similar from day to day, we ensure that schedules are repeatable (reasonably similar) by enforcing the constraint that final levels in tanks do not differ much from their initial conditions:

$$\begin{aligned} (h_{J,1} - h_{J,N}) \times A_J &\leq \delta_V, \\ (h_{J,1} - h_{J,N}) \times A_J &\geq -\delta_V, \end{aligned} \quad (9)$$

where δ_V defines the volumetric difference. This relaxes the approach where the final or initial tank levels would be input data, which would limit the feasible search space and potentially lead to a sub-optimal final solution. A similar initial and final constraint relaxation is used in [20] for Networks with fixed speed pumps, while [21] includes a penalty for final water levels below the initial level or for ones away from a specified target at the end of the operating period.

The energy balance for flows in pipes is modelled using a piecewise linear approximation of the head loss formulae given by either the Hazen-William or the flow dependent Darcy-Weisbach equations [22]. For a given time step, the head loss across pipe $P2$ connecting nodes $J3$ and $J4$, for example, can be approximated using a set of piece wise linear equations given by:

$$h_{J3} - h_{J4} = \begin{cases} q_{P2} m_{P2,1}^c + c_{P2,1}^c, & \text{if } q_{lim1} \leq q_{P2} \leq q_{lim2} \\ q_{P2} m_{P2,2}^c + c_{P2,2}^c, & \text{if } q_{lim2} \leq q_{P2} \leq q_{lim3} \\ \vdots & \\ q_{P2} m_{P2,5}^c + c_{P2,5}^c, & \text{if } q_{lim5} \leq q_{P2} \leq q_{lim6} \end{cases} \quad (10)$$

For a network node joining components $P_1, P_2, \dots, P_n$, the mass flow must balance at each time step j . This is given by:

$$q_{P1,j} + q_{P2,j} + \dots + q_{Pn,j} = 0 \quad (11)$$

In summary the variables of the optimisation problem are the binary variable T for the ON – OFF status of the pumps, $\mathcal{T}$ that describes the throttle of the pumps and h for the hydraulic head at a node and q for the volumetric flow rates in all links. Although not described here, a set of binary indicator variables are used to enforce the piecewise linear approximations for headloss across pipes [15]. For a WDS with variable speed drive pumps the general pump scheduling optimisation problem is given by:

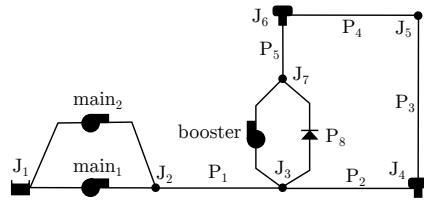
$$\begin{aligned} \text{min: } & f_1(\cdot) \\ \text{s.t.: } & (5), (6), (7), (9), (10), (11) \end{aligned} \quad (12)$$

For the demand response case, where the optimal level of DR power to provide is left to be found by the solver, the above formulation is modified to:

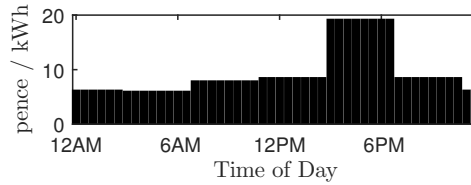
$$\begin{aligned} \text{min: } & f_1(\cdot) + f_2(\cdot) \\ \text{s.t.: } & (4), (5), (6), (7), (8), (9), (10), (11) \end{aligned} \quad (13)$$

2.3. Procedure

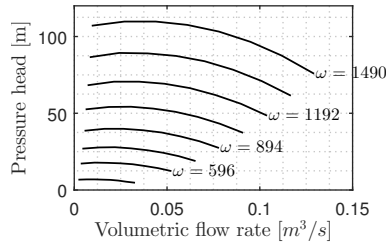
The focus of this research is how the financial viability of demand response provision differs between WDSs with or without variable speed drives fitted to the system pumps. The network investigated is the Van Zyl benchmark network, shown in Figure 1a, which is modified to be equipped with VSD pumps. The main pumps are replaced with pumps of type “Grundfos-NK-100-250” and the booster pump is replaced with a pump of type “Grundfos-NB-150-500”, the network and the changes made are further described in [24]. For the comparison to fixed speed operation the pump are modelled with $\mathcal{T} = 1$. The performance of the Grundfos-NB-150-500 pump is summarised in the characteristic curves in Figure 2



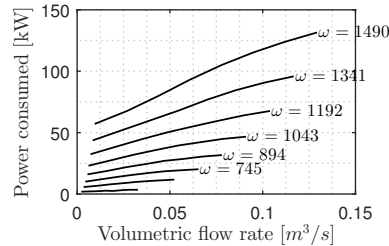
(a) The Van Zyl benchmark network adapted from Van Zyl et al.[23]



(b) Weekday electricity tariff of a UK water utility with $\frac{Price_{max}}{Price_{min}} = 3.2$



(a) Characteristic curves of a VSD pump. When modelled as a FSD pump only the curve $\omega = 1490$ is used.



(b) Power curves of a VSD pump. When modelled as a FSD pump only the curve $\omega = 1490$ is used.

Figure 2: Characteristic curves and power curves of the Grundfos-NK-100-250 pump, used as booster pump in the Van Zyl Network [16]

The operation of the WDS is investigated in different states by altering the pump utilisation rate, defined as the proportion of the overall demand of water to the best efficiency point operation of one of the *main* pumps. The pump utilisation rate has also been defined as the share of time the pumps operate during a day [25]. In this work we use the first definition as the operation times of the pump are found by the optimisation. For a range of pump utilisation rates and time-of-use peak price ratios (in the UK), we compare the operating cost, demand response revenue and GHG emissions of the network. To obtain a better understanding of the differences between a network offering DR from VSD pumps compared to a network with fixed speed pumps, only a small exert of the possible pump utilisation rates is examined, to enable a more detailed study of the behaviour.

To analyse the effect of peak price on the schedules and the financial viability of demand response services, we scale the tariff in Figure 1b by altering the minimum and maximum prices over a large range, while maintaining the same mean price for the tariffs to allow a fair comparison between different tariffs. Each electricity tariff used in our optimisation is thus referred to using the ratio of the maximum and minimum prices, $\frac{Price_{max}}{Price_{min}}$. The tariff used by the utility in Figure 1b has a ratio of 3.2.

3. Results

3.1. Operation of a VSD pump

Figure 3 shows the average operating cost across a range of pump utilisation rates. The results in Figure 3 agree with previous work examining the operating cost of VSD pump systems [16] and show a reduction in operating cost when operating the WDS with VSD pumps compared to the operation with FSD pumps. This difference is also reflected in the GHG emissions as shown in Figure 4. This indicates a better efficiency of the overall system when operating with VSD pumps. The dashed arcs indicate the operation when not participating in a STOR scheme.

In Figure 4 the GHG emissions of the system were computed by subtracting the GHG emissions that would be saved through the provision of STOR services from the GHG emissions of normal optimised operation without DR. The GHG emissions associated with an DR event are $88.3 \text{ CO}_2/\text{kW h}$ [10] while those associated with the OCGT are $777 \text{ CO}_2/\text{kW h}$ [26]. The WDS is assumed to provide STOR services regularly resulting in a provision of 137 kW h/kW/a [27]. This means that for each kW of power bid to the DR provision, over a year the WDS would expect to provide 137 kW h of reserve energy through STOR.

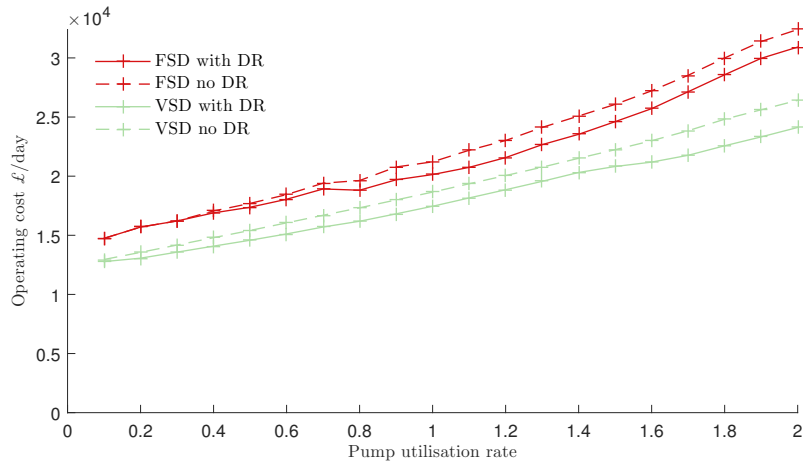


Figure 3: Operating cost for all pump utilisation rates, averaged across all $\frac{P_{max}}{P_{min}}$

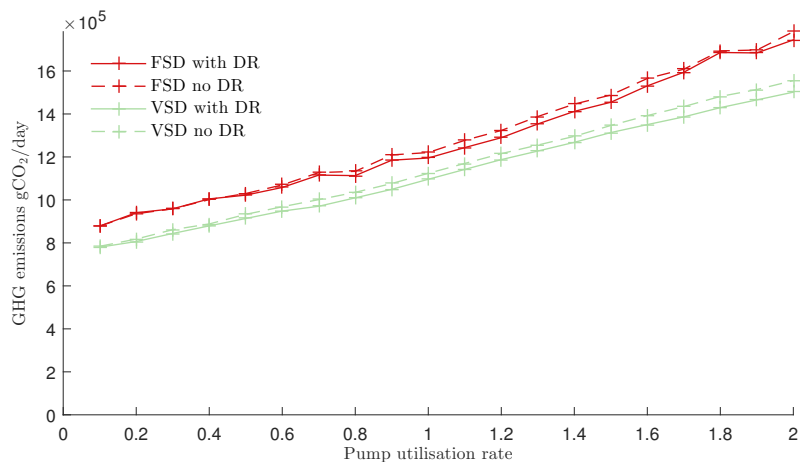


Figure 4: Mean GHG emissions averaged across all $\frac{P_{max}}{P_{min}}$

The operating cost and GHG emissions increase quasi linearly with the pump utilisation factor. The increase in cost and emissions for the FSD pumps is stepwise as certain changes in schedule are more expensive than others. The gap between the operating costs with and without demand response increases with pump utilisation rates since demand response becomes more profitable at higher pump utilisation rates.

3.2. Demand response from a VSD pump

The amount of pump power consumption committed to the provision of demand response differs significantly between the FSD pumps and the VSD pumps as shown in Figure 5. The power committed from the FSD pumps can only increase in steps that are the size of the pumps' power consumption. In the model used, there are pumps with 78 and 130 kW installed. The optimal power to commit for the VSD pumps increases monotonically and smoothly, i.e. without visibly large steps. At low levels of pump utilisation, where no FSD pump can provide demand response viably, Figure 5 shows that the VSD pumps can offer demand response. The optimal level of demand response provided by the VSD pump remains above or equal to that of the FSD pumps up to a pump utilisation rate of 1.1. For a pump utilisation rate in the range 1.1–1.6, the power committed to demand response from a FSD pump is larger, and above that the power committed from the VSD pumps. Beyond a utilization rate of 1.6, while the VSD pumps

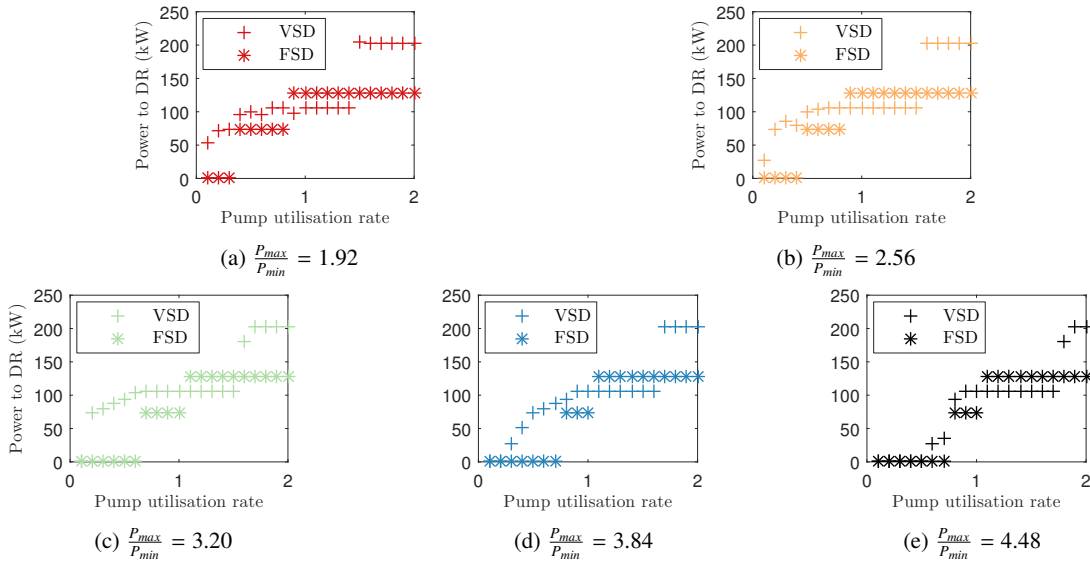


Figure 5: Optimal power committed to demand response for a range of price vectors

continue to increase their DR power provision, the FSD pumps cannot commit more power due to the stepwise nature of the pump power increments.

The optimal power to commit to demand response decreases a little for tariffs with larger $\frac{P_{max}}{P_{min}}$. The higher the ratio $\frac{P_{max}}{P_{min}}$, the more expensive the operation in peak times is compared to the rest of the tariff. This discourages operation in peak times and this reduces the financially viable options to change the schedule in order to accommodate DR services. For operations with a large pump utilisation rate the optimal pump schedule for operations with or without DR may look very similar, providing additional revenue and GHG emission reductions without a change in operations, except during a DR event. Stochastic DR events are not explicitly modelled here as we assume that a DR event for a WDS with VSD pumps does not differ from a DR event for a WDS with FSD pumps which have been modelled previously [10]. Here we assume that these optimal power levels for provision are bid and accepted by the aggregator or NG. The problem of stochastically modelling the bidding process and probability of subsequent acceptance is a difficult game theoretic problem with stochastic uncertainty. Such a study is beyond the scope of this paper.

4. Discussion

The results here confirm that the operating cost of a WDS are lower when operating with VSD pumps and providing demand response to the electricity grid through the STOR mechanism. The stepwise increases in committed power of the FSD pumps prevents a WDS with FSD pumps to offer response energy through a mechanism such as STOR if the pump utilisation rate isn't large enough. In the case of the Van Zyl network model considered here, the power consumed by the booster pump could be committed to the demand response scheme before the larger main pumps were committed. The same WDS equipped with VSD pumps could offer demand response at lower pump utilisation rates, using the extra income to reduce the operating cost even if only by a small amount (~5%). Comparing the operating cost with and without the provision of demand response, Figure 3 shows how the provision of demand response reduces the overall operating cost for the WDS equipped with FSD pumps and VSD pumps.

As shown in Figure 4, the GHG emissions of the WDS are considerably lower when operated with VSD pumps compared to operations with FSD pumps. Participation in a DR service can reduce the GHG emissions associated with the operation of the WDS even further by displacing other more polluting DR service providers such as OCGTs. The results confirm that a WDS operated with VSD pumps can further reduce the GHG emissions associated with the operation through the provision of a DR service such as STOR. Demand response events were not explicitly modelled here. As a WDS with VSD pumps could in theory bid a wider range power consumption reductions, this may create more opportunities to provide DR. This additional flexibility may make a WDS with VSD pumps a more attractive

participant in a DR scheme for an aggregator or network operator as it can adjust the power consumption more finely compared to a WDS with FSD pumps.

5. Conclusion

We formulate demand response provision from a WDS with VSD pumps and find the optimised pump schedule through a mixed integer linear problem formulation. This method provides a bound on the optimality, enabling a comparison between operating schemes, such as with or without demand response. We show that variable speed pumps not only enable operation at lower cost and lower GHG emissions due to the finer control of performance, but can also enable a WDS to participate in demand response schemes over a wide range of operating conditions. This opens up further revenue streams to reduce cost as well as opportunities to reduce the GHG emissions of the WDS. These results should encourage the retrofitting of VSDs to existing WDS and highlight another benefit of VSD pumps in new WDS.

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