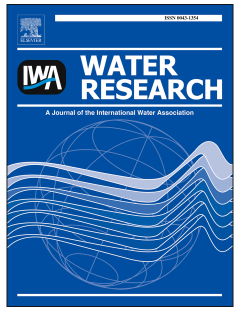

The Difference Between Energy Consumption and Energy Cost: Modelling Energy Tariff Structures for Water Resource Recovery Facilities

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ABSTRACT

The objective of this paper is to demonstrate the importance of incorporating more realistic energy cost models (based on current energy tariff structures) into existing water resource recovery facilities (WRRFs) process models when evaluating technologies and cost-saving control strategies. In this paper, we first introduce a systematic framework to model energy usage at WRRFs and a generalized structure to describe energy tariffs including the most common billing terms. Secondly, this paper introduces a detailed energy cost model based on a Spanish energy tariff structure coupled with a WRRF process model to evaluate several control strategies and provide insights into the selection of the contracted power structure. The results for a 1-year evaluation on a 115,000 population-equivalent WRRF showed monthly cost differences ranging from 7 to 30% when comparing the detailed energy cost model to an average energy price. The evaluation of different aeration control strategies also showed that using average energy prices and neglecting energy tariff structures may lead to biased conclusions when selecting operating strategies or comparing technologies or equipment. The proposed framework demonstrated that for cost minimization, control strategies should be paired with a specific optimal contracted power. Hence, the design of operational and control strategies must take into account the local energy tariff.

HIGHLIGHTS

- A framework to model energy tariff structures was proposed
- 7-30% difference was obtained when comparing TOU structure vs average energy price
- The framework was applied to compare aeration control strategies
- Proper selection of contracted power resulted in savings without investment

KEYWORDS: wastewater treatment; process control; energy costs; energy tariff; time-of-use; power demand; benchmark simulation model (BSM).

ABBREVIATIONS

Aerobic tank (AER)

Benchmark simulation model (BSM)

Contracted power capacity (PC_{P_i})

Dissolved Oxygen (DO)

Energy usage charges term (EUC_{term})

Energy consumption per tariff period (EC_{P_i})

Energy usage charge per tariff period (r_{VE,P_i})

External recirculation flow-rate (Q_{ras})

Fixed power charges term (FPC_{term})

Greenhouse gas (GHG)

High season charges (H)

Internal recirculation flow-rate (Q_{intr})

Kilowatt (kW)

Kilowatt hour (kWh)

Low season charges (L)

Moderate season charges (M)

National value-added tax (VAT)

Peak power demand charges term (PDC_{term})

Peak power demand charges factor rate (K_{P_i})

Proportional-integral controller (PI)

Proportional-integral-derivative controller (PID)

Population equivalent (PE)

Power demand measured (PD_{P_i})

Tariff period (P_i)

Taxation term (T_{term})

Time-of-Use (TOU)

Total ammonia (NHx)

Total energy cost (TEC)

Total nitrogen (TN)

Total number of tariff periods (P_n)

Very low season charges (VL)

Wastage sludge flow rate (Q_w)

Wastewater resource recovery facility (WWRF)

1. INTRODUCTION

The high interdependency between water and energy systems, population growth, climate change, urbanization, increasing living standards and food consumption requires a holistic evaluation and an integrated approach (Olsson, 2012a). As a result, efficient and sustainable management of water and energy systems have become a priority. Within this context, water and energy pricing structures (also called demand side management or demand response mechanisms) become crucial tools to control consumption and give incentives to customers to become efficient in the use of water and energy (Olsson, 2012a).

With regards to energy use, energy systems are sensitive to energy consumption spikes and therefore measures have to be taken either to optimize energy generation and distribution or better to reduce or shift peak power demands. While there is plenty of experience in optimizing energy generation and distribution, it is the demand side that is receiving increasing attention by research and industry (Palensky & Dietrich, 2011). Energy tariff structures are common demand-side management mechanisms used to improve the energy system in terms of consumption through the application of different energy pricing structures (e.g. time-of-use rates) and charges (e.g. energy usage, peak power demand charges) in the different billing terms. Those mechanisms incentivize the reduction or shift of peak power demands at specific times for a specific duration, avoiding investments in additional infrastructures by balancing energy use and, consequently, reducing greenhouse gas (GHG) emissions. As an example, the impact of such tariff structures in the Pennsylvania-New Jersey-Maryland Interconnection Regional Transmission authority (serving 60 million customers) was estimated by Spees and Lave (2006). The study concludes that even small shifts in peak demand would have a large effect on savings to consumers and avoided costs for additional peak capacity: a 1% shift in peak power demand would result in savings of 3.9% (billions of dollars at the system level). Such large reductions would be achieved after encouraging customers and industries to properly adjust their energy consumption and reduce peak power demands.

Water resource recovery facilities (WRRFs) were formerly referred to as wastewater treatment plants when they largely addressed waste disposal problems while their role as sources of energy and materials to be mined had not yet been fully recognised. WRRFs are large energy consumers, albeit minor societal contributors to the environmental footprint when compared to other manufacturing or human activity (Olsson, 2012a). Approximately 2-3% of the world's electrical energy is used for water supply and sanitation purposes, and 1-18% of the electrical energy in urban areas is used to treat and transport water and wastewater (Olsson, 2012a). The energy consumption of resource recovery ranges from 335 MWh.month^{-1} (WRRFs serving 100,000 population-equivalent or PE) up to 6,600 MWh.month^{-1} (WRRFs serving 3,000,000 PE), while the associated energy costs can range from 45,000 €.month^{-1} to 280,000 €.month^{-1}, respectively. Hence, WRRFs are suitable candidates for the implementation of measures to reduce peak power demand, contributing in this way to grid stability, decreased energy generation costs and reduced CO_2 emissions. WRRFs would also benefit monetarily, since their energy bill would be significantly reduced.

Several potential measures can be applied to reduce or shift the power demand of WRRFs. Flow and load equalization was evaluated as a strategy to shift power demand by Leu et al. (2009) for a case study in California. Their results showed decreased costs and even reduction of CO_2 emissions at the energy generation side. Another possible measure is aeration control, since aeration supply in WRRFs represents between 50 and 70% of process energy consumption (Reardon, 1995; Rosso and Stenstrom, 2005; WEF, 2009). Control of aeration has been successfully brought into practice with reductions in energy consumption as high as 30% (Olsson, 2012b; Amand et al., 2013). These reductions have been converted into monetary units by using an average energy price (*inter alia*, Cadet et al., 2004; Ekman et al., 2006; Samuelsson et al., 2007; Stare et al., 2007; Benedetti et al., 2008; Guerrero et al., 2011) or non-monetary units using the Operational Cost Index (Gernaey et al.,2014). However, until now no studies have incorporated energy tariff structures into the evaluation of control strategies or technologies in view of energy cost.

Energy demand-side mechanisms and energy tariff structures are a global trend and should be included in the evaluation of technologies and operational strategies (e.g. process control solutions). Thus, if a model-based approach has been chosen, the energy tariff structure needs to be included in the evaluation. Thus far, there still exists a gap between energy consumption and costs since there is no generalized cost model describing current energy tariff structures to evaluate operating costs at WWRFs. The energy market is very decentralized using utility-specific or clientspecific accounting functions to calculate energy bills. Within this context, a generalized cost model covering the major energy tariff terms enables a planning engineer to: i) Highlight critical situations where peak power demand charges are raising total energy costs; ii) Develop strategies to reduce energy consumption on a time-of-use basis and maximize energy production at peak periods; iii) Specify the appropriate equipment to reduce overall energy consumption and power demand; iv) Identify the critical terms in the energy bill and develop operating strategies to operate and control the plant for their reduction; and v) Find the optimal contracted power capacity structure for a specific plant.

The goal of this paper is to demonstrate the importance of incorporating more realistic energy cost models based on current energy tariff structures when evaluating operating strategies for WRRFs. For the first time within the WRRF community, generalized concepts on tariff structures are described in a systematic framework, and a generalized structure including the most common billing terms is presented. As a case study, a Spanish energy tariff structure was coupled with a WRRF process model to evaluate and compare several control strategies, thus providing insights into the selection of a specific contracted power structure. Finally, a discussion section is provided were the importance of considering energy tariff structures and future work are discussed.

2. ENERGY TARIFF STRUCTURES

A large variability of energy tariff structures can be found depending on: i) the customer category (i.e. residential or industrial, small or large customers); ii) the specific energy pricing structure applied; and iii) the different billing terms involved in the bill. In this section we describe the concepts of energy pricing structures and billing terms behind the most common energy tariff structures for large energy customers based on selected energy contracts obtained from different WRRFs in Europe and North America.

2.1. Energy pricing structures

The energy pricing structure defines how the various charge rates are applied to the different terms of the bill, such as the charges related to the energy usage (expressed for example in €.kWh^{-1}), contracting a specific power capacity (expressed as €.kV^{-1} or €.kW^{-1}) or peak power demand penalties (expressed as €.kW^{-1}). Descriptions of the three types of energy pricing structures identified are described below.

2.1.1. Flat rate structure (also called constant or fixed rate)

In a flat rate structure customers are charged the same amount for the energy they use or peak power demanded, no matter the time of the day or the quantity that is consumed. This is the simplest structure but rarely applied in energy contracts for large energy customers (e.g. WRRFs).

2.1.2. Time-of-Use rate structure (TOU) (also called time of day rate)

TOU rate structures are widely applied at utilities across the United States and Europe. In a TOU rate, customers are charged a different price according to the time of day, day of the week and/or season of the year. **Figure 1a** shows a conceptual example of a typical TOU rate structure where different rates (P1, P2 and P3) are applied depending on the time of day. Normally, in a TOU rate two or three price periods are applied and classified as On-peak or Peak (highest energy price of the day, e.g. P1), Mid-peak or Shoulder Peak (e.g. P2), and Off-peak (lowest energy price of the day, e.g. P3). The On-peak and Mid-peak periods are usually applied during the day (when the highest energy demand occurs), and the Off-peak periods during the night. The mechanism encourages customers to shift their power demand from peak periods (with high prices) to off-peak periods (with low prices). On the other hand, charge rates applied during the day can vary depending on the season or month. In the majority of the evaluated cases, a winter and summer TOU tariff schedule is defined such as in the US (e.g. Southern California Edison), where different prices and periods are applied in winter and summer, respectively. In other cases, the TOU tariff schedule can change depending on the month, such as in Spain (Royal Decree 1164/2001). TOU rates are of special interest for WRRFs since usually high energy usage and power demand is linked to high load periods, usually coinciding with the highest energy price periods.

2.1.3.Tiered rate structure (also called step rate or block rate)

In a tiered structure (see **Figure 1b**) customers are charged a different price based on the amount of energy used or the maximum peak power demand claimed. Various tariff blocks are defined (B1, B2 and B3), where each block is charged at a different price (P1, P2 and P3). In this way, when companies have reached the cap of their first block, any additional electricity used is charged at their second block price and so on. Depending on the type of tariff contracted, prices can increase (i.e., tiered rate) or decrease (i.e., inverse tiered rate) for the amount of energy consumed. Examples of tiered rate structures can be seen in the US (e.g. Direct Energy Business), Canada (e.g. Hydro One) and Australia (e.g. Energy Australia).

2.2. Billing terms: Understanding the electrical bill

The electrical bill that customers receive includes several terms, which may vary according to the specific energy tariff structure contracted. The five most common terms are summarized below.

2.2.1 Fixed charges (also referred to as customer charges, fixed fee, fixed standing charges, or metering charges)

The fixed charges usually cover the costs of access, metering, meter reading, billing and other customer-related operating costs. The fixed charges for each power meter [e.g. in €.month^{-1} or €.(meter.month)$^{-1}$] are for supplying electricity to the customer premises for each day of the billing period, regardless of how much electricity is used or peak power is consumed.

2.2.2. Fixed power charges (also referred to as power fee, contract fee, or power capacity charges)

The fixed power or capacity charges usually cover the costs associated with the power generation and distribution. The fixed power or capacity charges are the charges to be paid depending on the defined contracted power structure, such as based on the contracted voltage [e.g. €.(kV.month)$^{-1}$] or the contracted power capacity [e.g. €.(kW.month)$^{-1}$]. A large variability of rates and energy tariff structures (see Section 2.1) can be applied depending on a number of factors (e.g. policies, regulations, electrical company, customer category, or contracted power capacity).

2.2.3 Energy usage charges (also referred to as energy charges, consumption charges, transmission fee, or electricity supply charges)

The energy usage charges usually are related to the costs sustained by the power utility for delivering electric energy to the customer, including operating and maintenance expenses of the electrical grid. The energy usage charges is varying depending to the quantity of energy consumed during the billing period (kWh), taking into account the kilowatt-hour price (e.g. €.kWh^{-1}). This term is variable depending on the amount of energy that is consumed and the energy pricing structure applied (see Section 2.1), and it often has the largest impact on the billed price.

2.2.4 Peak power demand charges (also referred to as demand, distribution demand, penalty, or overuse charges)

Peak power demand charges are common demand side management mechanisms used to cover the extra costs for excessive power consumption within a specified short period of time. The peak power demand charges are usually based on the maximum peak power demand (kW) measured in any time interval (e.g. 15min, 30min, or 60min), in most cases during a monthly billing period or during the previous 11 months, such as in the United States (e.g. Dominion Virginia Power VEPGA). There are different ways to apply peak power demand charges as shown in **Figure 2**. In the majority of cases such as in the United States (e.g. Southern California Edison) or in Sweden (e.g. Vattenfall), the peak power demand charges are determined based on the maximum peak power demand measured in a billing period (case A, **Figure 2**). In other cases, such as in Spain (Royal Decree 1164/2001), in the United States (e.g. Dominion Virginia Power VEPGA), in Sweden (e.g. E.ON Energy Company, Tekniska Verken) or Canada (e.g. Hydro Quebec), the peak power demand charges are adjusted based on the difference between the maximum peak power consumed and the contracted power capacity (case B, **Figure 2**), corrected with the fixed power charges or sometimes integrated in the same billing term. If the maximum peak power consumed exceeds the contracted power, charges will be applied. For cases A and B, in order to compensate for recovering the costs of providing higher peak consumption and to discourage power demand, utilities bill the penalty charge over a monthly or quarterly cycle. This means that even though the peak power demand may only occur over a brief period of time, the customer is charged a penalty fee over a longer term. Another peak power demand charge is to apply a penalty every time the peak power demand is above the contracted power capacity (case C, **Figure 2**), such as in Spain (i.e. Royal Decree 1164/2001). Hence, the more power is consumed above the contracted power capacity, the more penalizations are applied.

2.2.5. Reactive energy charges (also referred to as reactive power factor or reactive power fee)

The reactive energy charges cover the costs for the energy or power dissipated by inductive electrical equipment, measured as reactive energy (kVArh) or reactive power (kVAr). The reactive energy charges are referred to the price that has to be paid when there is an excess consumption of reactive energy or power. In other words, the reactive energy charges are the charges for the inefficiency at the customer's site. The level of inefficiency is usually expressed as a percentage and is called power factor (ratio between active power and apparent power). In cases such as in Spain (Royal Decree 1164/2001), the level of inefficiency is expressed as a function of the cos(φ) value, where φ is the angle of difference (in degrees) between the active power and apparent power, which is the quantification of the departure between 1.0 (ideal condition where only non-reactive power is drawn or the electrical system is fully re-phased) and the actual customer condition (<1.0). These charges are site-specific and respond to the properties and status of the electrical equipment. A way to reduce or eliminate reactive energy charges can be by installing e.g. capacitors or replacing existing equipment (e.g. motors, transformers, or other energy consumers) with more energy-efficient equipment.

2.2.6. Taxes

Taxes are site-specific and can include: customer taxes, energy commission taxes, regulatory taxes, delivery taxes, or green energy taxes.

3. MODELLING THE TOU TARIFF STRUCTURE FROM SPAIN AND ASSESSMENT OF CONTROL STRATEGIES

This section introduces a case-study for a typical WRRF in Spain for which the Spanish energy tariff structure was modelled in detail.

3.1. Water Resource Recovery Facility under study

A typical WRRF receiving a load of 115,000 population equivalents at an average flow of 18,166 $m^3.d^{-1}$ was modelled in SIMBA# (ifak e.V., Germany) using the Benchmark Simulation Models (BSM) principles (Gernaey et al., 2014). The layout (**Figure 3**) is based on the BSM1_LT layout, but employing the BSM2 layout reactor volumes (Gernaey et al., 2014). A tapered diffuser system was modelled with a resulting airflow split of 50% to AER1, 30% to AER2 and 20% to AER3. The original BSM blower and pump models were substituted with more detailed ones (SIMBA#, 2014). The models include variable efficiency curves, capacity bounds, and parameters to mimic different types of equipment. In this case-study the model parameters were set to a constant efficiency to facilitate the results evaluation. The energy efficiency models for pumping, mixing and aeration were calibrated to achieve an energy consumption of 0.6 $kWh.(PE.y)^{-1}$, 1.8 $kWh.(PE.y)^{-1}$, and 13.7 $kWh.(PE.y)^{-1}$ respectively (Müller et al., 1999). As only the energy consumption for aeration and pumping (return activated sludge and internal recycle, wastage) was modelled, an additional constant energy consumption of 5,543 $kWh.d^{-1}$ was added to account for the extra 50% of energy (e.g. for influent pumping, heating, lighting) that a WRRF of that magnitude would consume (see **Figure 4**), which falls within the Spanish TOU-6.1 rate energy tariff structure for large energy customers (Royal Decree 1164/2001 and Order ITC/2794/2007) (see Section 3.3). The dynamic BSM1_LT influent profile of 609 days (including dynamic temperature) was simulated and the last 364 days were used for evaluation purposes (Gernaey et al., 2014).

3.2. Evaluated aeration control strategies

In this study three aeration control strategies based on DO and total ammonia (NH_x) measurements were implemented in SIMBA#, evaluated and compared for effluent quality, energy consumption and costs. Two different waste sludge flow rates (Q_{w_winter} = 300 $m^3.d^{-1}$; Q_{w_summer} = 400 $m^3.d^{-1}$) were imposed depending on the time of the year in order to sustain the nitrifying biomass in the system during the winter period. The external (Q_{ras} = 18,446 $m^3.d^{-1}$) and internal (Q_{intr} = 55,338 $m^3.d^{-1}$) recirculation flow-rates remained constant throughout the simulations.

Base Control Strategy: DO_{PI} control. The DO concentration in reactor AER2 is measured and fed to a PI controller, which is manipulating the total airflow to maintain a set-point of 2,5 g DO.m^{-3}. This controller aims at achieving optimal conditions for all aerobic processes.

Control Strategy 1: $NH_{x,On\text{-}Off}$ control. A master controller is put on top of the DO PI controller (slave). The master activates or inactivates the DO PI controller after comparing the ammonia (NH_x) concentration in the last aerobic reactor (AER3) with the desired NH_x set-point. The DO PI controller is switched On when the ammonium concentration is above 3.5 g NH_x-N.m^{-3} and switched Off when lower than 2.5 g NH_x-N.m^{-3}. If On, the DO PI controller uses a DO set-point of 2.5 g DO.m^{-3}.

Control strategy 2: $NH_{x,PID}$ control. The total ammonia concentration in the last aerobic reactor (AER 3) is controlled at 3 g NH_x-N.m^{-3} with a master PID controller that adjusts the DO set-point for reactor AER2 between 0.1 and 2.5 g DO.m^{-3}.

3.3. TOU tariff from Spain

The energy cost model was implemented in the MATLAB® platform and replicates a Spanish TOU-6.1 rate structure for large energy customers (Royal Decree 1164/2001 and Order ITC/2794/2007). The TOU-6.1 rate structure is applied for a contracted voltage between 1kV and 36kV and a contracted power capacity over 450 kW. The TOU-6.1 rate structure consists of five billing terms: i) energy usage charges; ii) fixed power charges; iii) peak power demand charges; iv) reactive energy charges; and v) taxes. In this study the reactive energy charges were not included since these are site-specific (depending on the level of inefficiency of inductive electrical equipment of the customer's site) and we assume that the facility has a proper installation of these capacitors in place and there is no reactive energy. In the following sections the tariff schedule, the tariff rates and the energy cost calculations based on the different billing terms are described.

Tariff schedule. For the selected TOU rate structure six tariff rates (from P1 to P6) are applied during the year, but maximum three tariff rates are applied at different times of the day during a monthly billing period (see **Table 1**). On a monthly time-frame, the rates of charges applied can be classified as High (H), Moderate (M), Low (L), and Very Low (VL). The highest season charges (H) are applied during the beginning of summer (i.e. June and July) and winter seasons (i.e. December, January and February), coinciding with the highest energy demand periods of the year (e.g. increase of energy demand due to the heating/air-conditioning of households and industries). The moderate season charges (M and L) are applied during autumn and spring seasons, when the energy demand is moderate. Finally, the lowest charges (VL) are applied during holiday seasons (e.g. August), when the energy demand significantly decreases. On an hourly timeframe, the regulation of charges is performed according to the energy demand rates and the energy generation capacity during the day. The rate of charges applied can be grouped as On-peak (P1 and P3), Mid-peak (P2, P4 and P5) and Off-peak charges (P6). On-peak charges are usually applied to the highest demand periods of the day, coinciding also with the more expensive forms of electricity production (see **Table 1**). Mid-peak charges are usually applied during moderate energy demand periods. Finally Off-peak (such as night periods and weekends) charges are applied when demand is low and less expensive sources of electricity are used.

Tariff rates. The rates applied to the energy usage, the fixed power, and the peak power demand terms are presented in **Table 2**. These rates were obtained from a real energy contract of a WRRF and established by the electricity supplier according to the

Spanish legislation on average electricity tariff prices (Order IET/1491/2013). Energy usage charges span a 2.5-fold range (from 6.58 c€.kWh^{-1} to 16.4 c€.kWh^{-1}), fixed power charges span a 6-fold range [from 2.83 €.(kW.y)$^{-1}$ to 16.92 €.(kW.y)$^{-1}$], and peak power demand charges span a 6-fold range (from a factor of 0.17 to 1.0).

Energy cost calculation. The *energy usage charges* (EUC_{term}) are calculated using **Eq. 1** from the summation of the different energy consumption terms (EC_{P_i} in kilowatt hours - kWh) and multiplied by the corresponding charges (r_{VE,P_i}) for the different tariff periods (P_i), where P_n is the total number of tariff periods applied in the electricity contract.

$$EUC_{term}\left[\frac{€}{month}\right] = \sum_{P_i=1}^{P_n} \left(EC_{P_i} \cdot r_{VE,P_i} \right) \quad \textbf{(Eq.1)}$$

The *fixed power charges term* (FPC_{term}) is the cost of selecting a specific contracted power capacity for the different tariff periods. This is the summation of the product between contracted power capacity (PC_{P_i}, in kilowatt - kW) and charge (r_{FP,P_i}), for each tariff period. The total charges for the entire year are calculated, but then the payment is executed proportionally every month (**Eq. 2**). If the maximum peak power measured exceeds the contracted power capacity, then peak power demand charges are applied (see below).

$$FPC_{term}\left[\frac{€}{month}\right] = \sum_{P_i=1}^{P_n}(PC_{P_i} \cdot r_{FP,P_i}) \cdot \left(\frac{1year}{12moths}\right)$$ **(Eq. 2)**

The *peak power demand charges term* (PDC_{term}) is applied every time that the peak power measured (PD_{P_i}, in kilowatt - kW) in a 15 minute time interval exceeds the contracted power capacity (PC_{P_i}, in kilowatt - kW) for each tariff period (**Figure 2**, Case C). The penalizations are accumulated and applied through the **Eq.3**, only when the PD_{P_i} is greater than the PC_{P_i}. The total penalization is the summation of the n times of power penalized and multiplied for the specific charge factor rate (K_{P_i}) for each tariff period (see **Table 2**), where 1.4064 €.kW^{-1} is the corresponding charge applied per unit of power penalized.

$$PDC_{term}\left[\frac{€}{month}\right] = \sum_{P_i=1}^{P_n}\left(1.4064 \cdot K_{P_i} \cdot \sqrt{\sum_{j=1}^{j=n}(PC_{P_i} - PD_{P_i})^2}\right)$$ **(Eq. 3)**

A *taxation term* (T_{term}) is applied to the sum of the variable energy, the fixed power, and the penalty term. In Spain, the tax on electricity is 4.28% and the national value-added tax (VAT) is 21% applied on the taxed gross. Hence, the *total energy cost* (TEC) is the resulting sum of the different charge terms, as defined in **Eq. 4**:

$$TEC\left[\frac{€}{month}\right] = EUC_{term} + FPC_{term} + PDC_{term} + T_{term}$$ **(Eq. 4)**

4. RESULTS

4.1. Information provided by the new energy cost model

In this section an illustrative example of the implemented energy cost model for the one year simulation period of the Base Control Strategy (DO PI controller, DO_{PI}) is presented. In this study, 500 kW of contracted power capacity is selected for all tariff periods (P1 to P6).

4.1.1 Billing terms contribution for each month

Figure 5 shows monthly costs (split amongst the different billing terms) over the one year simulation of the DO_{PI} strategy. The results of the energy cost model show a large variability in costs (from 30,068 to 52,748 €.month^{-1}) (see stacked bar in **Figure 5**). The billing terms contributing most to the overall energy costs are the energy usage charges (accounting for 69% to 74% of the monthly total energy costs), followed by the total taxes (~ 21%), the fixed power charges (4 to 7%) and finally the peak power demand charges (0 to 5%). With regards to the variability of these terms, the fixed power is the only term that remains constant throughout the year, while the energy usage, the peak power demand charges and taxes are particularly variable.

4.1.2 Comparing the real energy cost model with an average energy price

The real cost model is compared with the case of using an average energy price (see line in **Figure 5**) of 12 c€.kWh^{-1}, calculated based on the total costs and the total energy consumed for one year simulation of the selected Base Control Strategy. The costs obtained when using an average energy price are only depending on the energy consumption and therefore show less variability over the months (from 37782 to 42411 €.month^{-1}). A control scenario evaluation using a simplified cost model based on an average energy price would therefore result in cost differences of 7 to 30% when compared to the real energy cost model, with significant over-estimation (30% in August, coinciding with the lowest rates) and under-estimation (22% in July, coinciding with the highest rates). The main reason for the differences between real cost models and average energy prices stems from the rates applied to the energy usage and peak power demand charges (see **Table 1** and **Table 2**), which are much higher during On-peak periods when compared to Off-peak periods. The rates for the peak power demand charges are 6 times higher during Off-peak periods, but with less contribution (1-5%) compared to the energy usage charges (69-73%). The "average energy price" used in the comparison is calculated from the total energy cost and the total energy consumed for the Base Control Strategy over the whole evaluation period (1 year), and therefore the annual difference between the proposed energy cost model and the average energy price is zero.

4.1.3 On-peak, Mid-peak and Off-peak contributions to the energy usage charges

Figure 6 shows the monthly total energy consumed distributed by tariff periods (**Figure 6a**) and the related energy usage charges (**Figure 6b**). The total energy consumed (**Figure 6a**) remains close to 363 $MWh.month^{-1}$ (coefficient of variation of 0.03) with around 16% during the On-peak periods, 24% during the Mid-peak periods, and 55% during the Off-peak periods. With regards to the energy usage charges (**Figure 6b**), larger variability compared to the total energy consumption was observed (21,518 to 37,294 $€.month^{-1}$) corresponding to a coefficient of variation of 0.17.

4.1.4 On-peak, Mid-peak and Off-peak contributions on the peak power demand charges

Figure 7 shows the total power penalized distributed by tariff periods (**Figure 7a**) and the related peak power demand charges (**Figure 7b**). The total power penalized (**Figure 7a**) is highly variable during the year ranging from 2.7 to 3,045 $kW.month^{-1}$.

With regards to the distribution of the power penalties through the different tariff periods, between 36-49% is assigned to On-peak periods, 36-43% to Mid-peak periods, and around 19% to Off-peak periods. Regarding the related costs, peak power demand charges (**Figure 7b**) are highly variable during the year (from 32 to 2,342 €.month^{-1}). It is worth noting that during the winter period the penalizations are very low which is related to the response of the DO PI control under low temperatures which is smoother.

4.2. Evaluation of aeration control strategies using the new cost model

In this section the results for the two ammonia-based aeration control strategies are compared against the Base Control Strategy and evaluated for the one year simulation period and maintaining the selected contracted power capacity of 500 kW for all the strategies.

4.2.1 Evaluation of system performance

Figure 8 shows the yearly average results obtained in terms of system performance and costs for the DO_{PI}, $NH_{x,ON/OFF}$ and $NH_{x,PID}$ controllers. The yearly average total NH_x concentration for the DO_{PI} controller (targeting full nitrification) is approximately 1.0 g NH_x-N.m^{-3}. Full nitrification could not be reached due to the high variability of the influent NH_x load compared to the slow changing mass of active nitrifiers (Rieger et al., 2014). The total nitrogen concentration is approximately 12.8 g NH_x-N.m^{-3} (**Figure 8a**). By introducing an NH_x controller the yearly average NH_x concentration increases (the total ammonia set-point for the $NH_{x,PID}$ is set to 3.0 g NH_x-N.m^{-3} and the switching criteria for the $NH_{x,ON/OFF}$ controller are set to 2.5 - 3.5 g NH_x-N.m^{-3}). At the same time total nitrogen (TN) decreases by 25%, reaching 9.5g

$N.m^{-3}$. The $NH_{x,ON/OFF}$ and $NH_{x,PID}$ controllers reduce aeration energy consumption by 7% and 18%, respectively, when compared to the DO_{PI}. When considering the total energy consumption in the WRRF, the savings translate to 3 and 7%, respectively, when compared to the DO_{PI}. Overall, the $NHx_{,PID}$ controller shows the best results in terms of nitrogen removal and energy consumption, followed by the $NHx_{,ON/OFF}$ and the DO_{PI} controllers.

4.2.2. Evaluation of the energy costs

Figure 8b shows the energy costs for one year obtained after simulating the three aeration control strategies using the new energy cost model (coloured bars) and compared with the case of using an average energy price (shadowed bars). The results indicate that the best control strategy is still the $NH_{x,PID}$ (461,717 €.y^{-1}), resulting in 9% and 5% lower costs when compared to the DO_{PI} (485,014 €.y^{-1}) and the $NHx_{,ON/OFF}$ (508,693 €.y^{-1}), respectively. With the new and more realistic energy cost model, the total energy costs for the $NH_{x,ON/OFF}$ controller are even higher than the Base Control Strategy due to the high impact of the penalization term (see **Figure 8b)**. PID or PI control strategies have a more attenuated response to disturbances than the digital On/Off control strategy, thus avoiding a sharp switch in DO set-points and consequently a sudden acceleration or turn-down of the blowers. Hence, the selection of best operating strategies (or in this case control strategies) cannot only rely on energy consumption, but should include variable energy pricing structures and the different billing terms.

4.3. Scenario analysis for selecting the optimal contracted power capacity

The energy market is highly dynamic and we observe a tendency to increase rates, especially for the fixed power and peak power demand terms. For instance, Albadalejo and Trapote (2013) studied the effects of electricity tariffs on the operating costs of WRRFs in Spain, concluding that the revision of the electricity rates between 2009 and 2012 have resulted in increases of electricity costs of 64.5% and 79% for small and large WRRFs, respectively. This caused an increase of electricity costs of the overall operating costs from 44% to 56%. As a consequence, this has motivated WRRFs to revise their electricity contracts by adjusting the contracted power capacity (hence, decreasing the charges for the fixed or the penalty charges in the bill). However, when lowering the contracted power the risk of getting penalization increases. Such a trade-off can only be properly assessed using a realistic energy cost model as shown in **Figure 9**.

For the case-study presented before different contracted power values (from 500 kW to 800kW) were evaluated for the tested control strategies. **Figure 9** shows the results in terms of total energy costs (**Figure 9a**), the peak power demand charges (**Figure 9b**) and the cost differences with an average energy price (**Figure 9c**). The results show that total costs (**Figure 9a**) can be reduced by finding the optimal contracted power which is 550 kW for the DO_{PI}, 600 kW for the $NH_{x,PID}$ and 750 kW for the $NH_{x,ON/OFF}$ controllers. Peak power demand charges can significantly be reduced by increasing the contracted power capacity (**Figure 9b**), although at the expense of a slight increase in fixed costs. Hence, savings of 5,335 €·y^{-1} or 1% can be achieved for the DO_{PI}, 26,333 €·y^{-1} or 5% for the $NH_{x,ON/OFF}$, and 8,124 €·y^{-1} or 2% for the $NH_{x,PID}$ controllers, when comparing to the default contracted power of 500kW. After considering the increase in the contracted power capacity the aeration control strategy resulting in the lowest costs is still the $NH_{x,PID}$ strategy with savings of ~6% when compared to the $DO_{,PI}$ and the $NH_{x,ON/OFF}$ controllers.

Finally, **Figure 9c** shows the percent difference between the energy cost resulting from the constant energy price and the proposed realistic energy cost model. The results show that the percentage is not constant depending on the contracted power and the aeration strategy. Using a simplified cost model based on averages would result in an average monthly cost difference of 13-15% when compared to the realistic energy cost model. A monthly cost deviation of 6-10% was calculated depending on the specific month, the control strategy and the contracted power selected. A maximum difference of 25% was reached for the $NH_{x,ON/OFF}$ at 500 kW contracted power.

5. DISCUSSION

5.1 Importance of considering energy tariff structures

This paper presents a framework to model energy tariff structures and a case study demonstrating the importance of taking energy tariff structures into account when comparing control strategies or technologies in WRFFs. In most energy studies the energy cost is produced by multiplying the energy consumption by an average energy price. However, we demonstrate here that operating costs depend significantly on the energy tariff structure applied, where different energy pricing structures (e.g., TOU) and/or peak demand penalty charges may alter substantially the cost efficiency of a control strategy. Therefore, reducing energy consumption does not necessarily mean reducing energy costs, and hence proper cost models are required to select the best control strategy.

The implementation of energy tariff structures offers the opportunity to better understand the energy costs of WWRFs, thereby being able to build an operational strategy through which the minimization of energy costs is obtained while maintaining the required effluent quality. First, the main energy cost contributors should be identified by analysing: i) the energy dynamics; ii) the impact of the energy tariff structure applied; iii) the way the different terms are calculated; iv) the role of the power terms and their contributions; and finally v) the potentials for further energy cost minimization. Then, several measures could be applied, including: i) avoiding peak power demand, especially during On-Peak periods; ii) shifting energy consumption from On-peak to Off-peak periods; and/or iii) coordinating in-plant power generation to reduce peak demands. The first option implies setting proper maximum boundaries for the controller settings together with proper selection of the contracted power capacity. The second option ranges from inexpensive measures (e.g., changing controller set-points and parameters for the different periods) to more expensive measures such as the construction of equalization basins, where possible. The third option could be coordinated on a plant level or even on an electrical grid level by shifting the control of biogas-fuelled generators to the energy provider. The plant should then benefit from a reduced energy tariff.

5.2 Outlook

The consideration of energy tariff structures in the management of WWRFs is the next natural step especially for WWRFs. Hence, depending on the effluent limits established, while maintaining the effluent limits below the never-to-exceed limits, a wide range of operational strategies could be applied (see previous section). On the other hand, a wide range of energy tariff structures can be found with different energy pricing structures (e.g., TOU, Tiered) and different ways to apply peak power demand charges. Within this context, further work is needed in the evaluation of the benefits and effects on energy costs of combinations of the above listed options.

Finally, the interdependency of water and energy systems is undeniable and opens the opportunity for better management of both. This is of special importance with WWRFs where the highest energy consumption usually coincides with the highest peak demand load on the power grid, thus coinciding with the highest energy price periods. Hence, reducing peak power demand in a short periods when energy cost are highest will also benefit the energy system by reducing grid load and GHG emissions (due to the need for more carbon-intensive energy sources during peak power demand periods). The impact of reducing peak demand in urban wastewater systems and the resulting benefits in the energy system in terms of energy generation costs and GHG emissions should be studied. These studies would be even more pertinent to regions experiencing extended droughts, since the ability to generate power depends on that of water, and water-stress conditions may imply limits on the ability for power utilities to deliver peak demand.

6. CONCLUSIONS

This paper demonstrates the importance of incorporating realistic cost models for the operational optimization of WRRFs. A new energy cost model based on actual energy tariffs was introduced and as a case study a Spanish tariff was successfully tested on a benchmark platform to evaluate different control strategies. It was demonstrated that the use of an average price for energy cost evaluation of WRRF operating strategies does not provide realistic costs. For the case study evaluated, monthly cost differences of 7 to 30% were observed compared to the proposed realistic energy cost model for a

WRRF operating with a DO PI control strategy. In the evaluation and aeration control strategies, it was demonstrated that using average energy prices and neglecting energy tariff structures may lead to biased conclusions when selecting operating strategies (e.g. control solutions) or comparing technologies or equipment. The results also demonstrated that selecting the optimal power contracted is a key issue since different operating strategies result in different optimal contracted power, and hence, proper energy cost models are required.

Energy cost calculations are very site-specific and it is therefore important to take into account the local energy tariff when evaluating operational strategies or selecting technologies or equipment. The proposed generic energy tariff model structure has been derived from various tariffs from around the world and can be used to implement individual energy tariffs.

7. ACKNOWLEDGMENTS

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TABLES

Table 1 - Tariff periods distribution during week days applied in a TOU-6.1 energy tariff structure (powers contracted up to 500kW) from the peninsula's Spanish Electricity System. During weekends (from 0 to 24h) only the P6 tariff period is applied. Months are classified based on the charges depending of the tariff rates applied (VL = Very Low, L = Low, M = Medium, and H = High).

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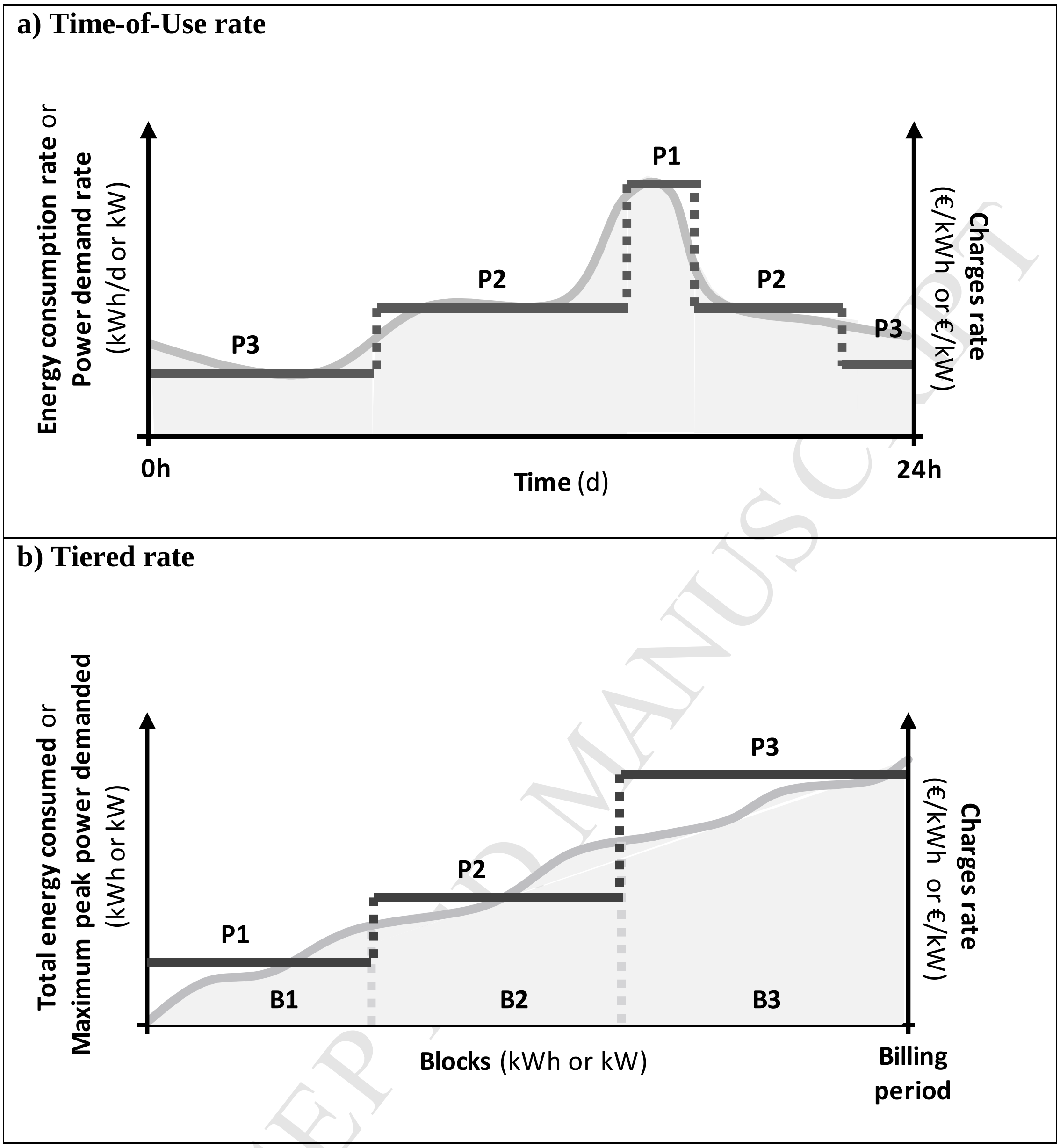
	Hours of the day (h)																								Season
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
January	P6								P2		P1			P2					P1			P2			H
February	P6								P2		P1			P2					P1			P2			H
March	P6								P4								P3						P4		M
April	P6								P5																L
May	P6								P5																L
1-15th June	P6								P4	P3						P4									M
16-30th June	P6								P2			P1							P2						H
July	P6								P2			P1							P2						H
August	P6																								VL
September	P6								P4	P3						P4									M
October	P6								P5																L
November	P6								P4								P3						P4		M
December	P6								P2		P1			P2					P1			P2			H

Table 2 - Unit charges applied for a TOU-6.1 energy tariff structure for a real WRRF - High Voltage power contract of 500 kW

Unit charges	P1	P2	P3	P4	P5	P6	Units
Energy usage rates (r_{VE,P_i})	16.4	13.2	11.0	8.6	8.0	6.58	c€.kWh^{-1}
Fixed power rates (r_{FP,P_i})	16.92	8.47	6.20	6.20	6.20	2.83	€.(kW.year)$^{-1}$
Peak power demand rates (K_{P_i})	1	0.5	0.37	0.37	0.37	0.17	-



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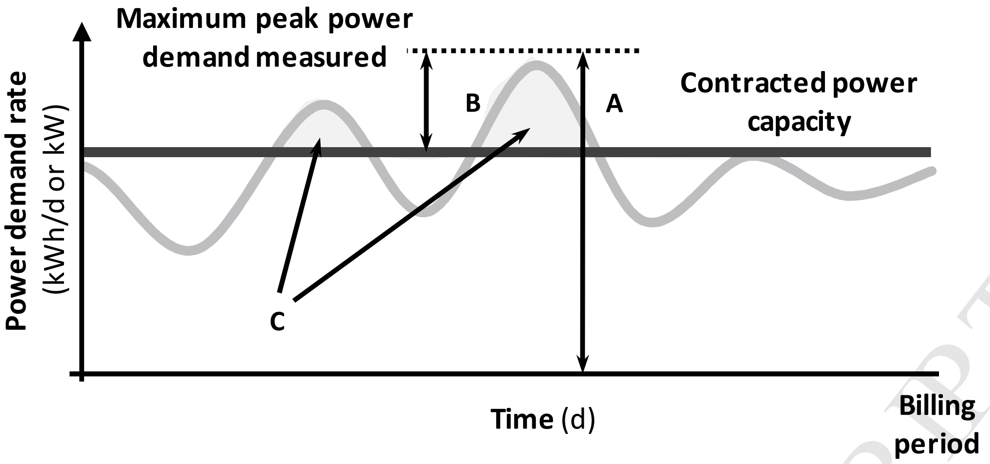

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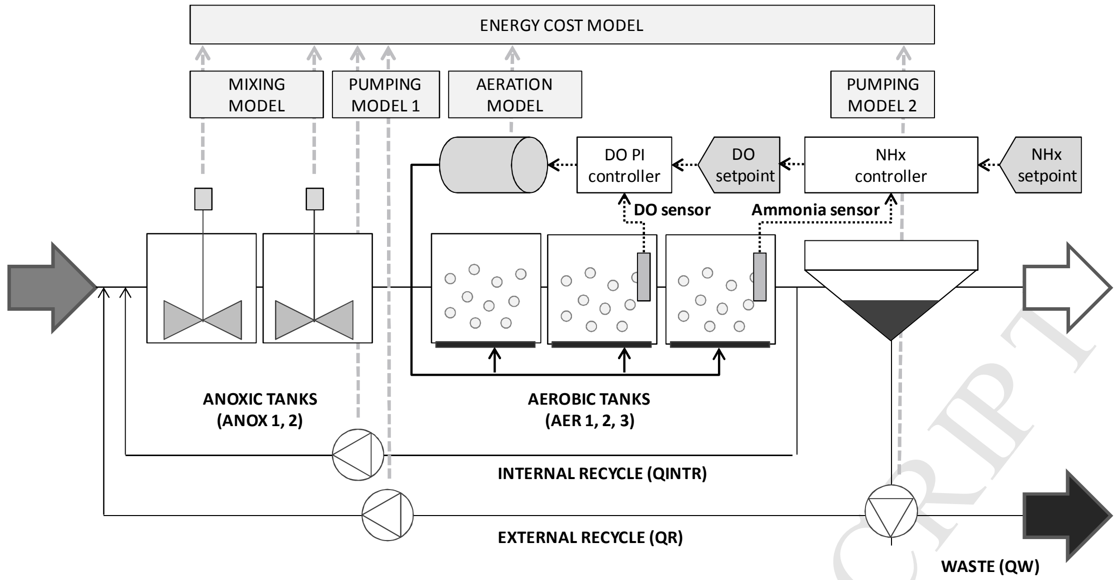

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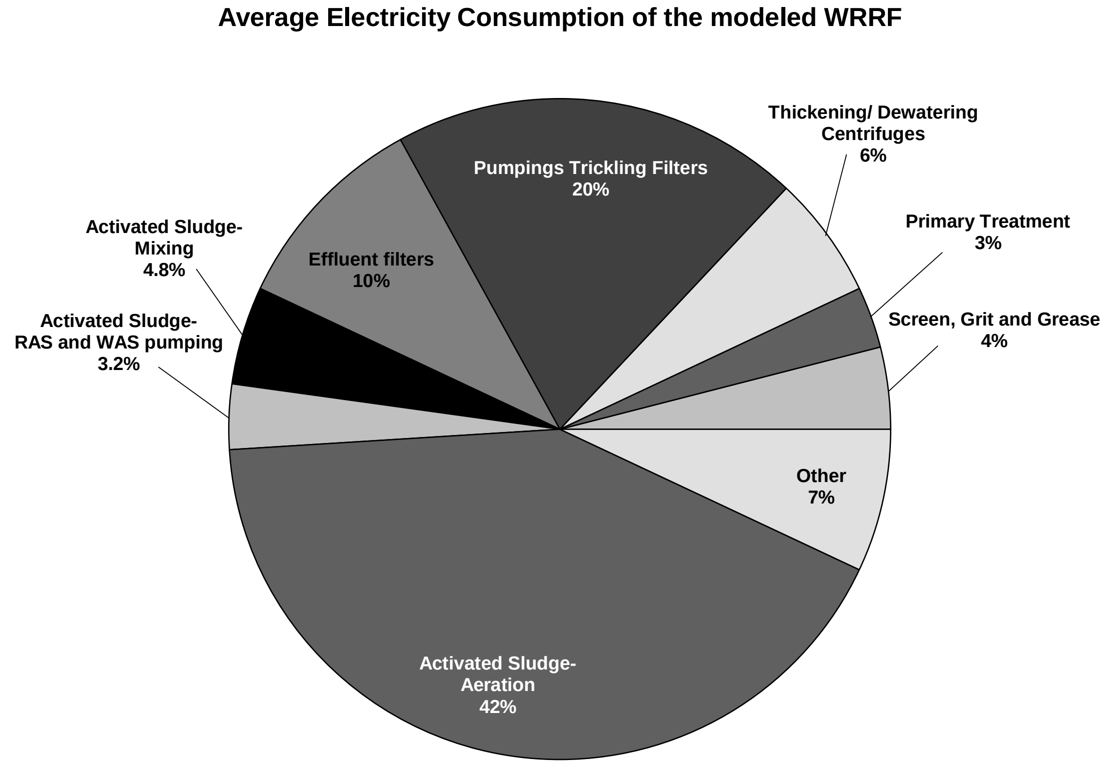

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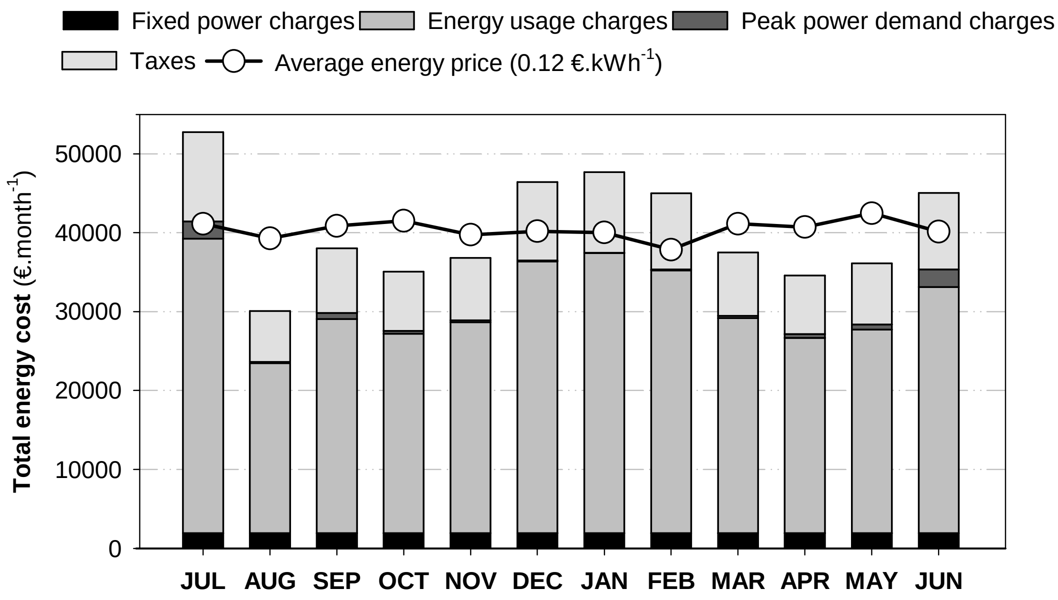

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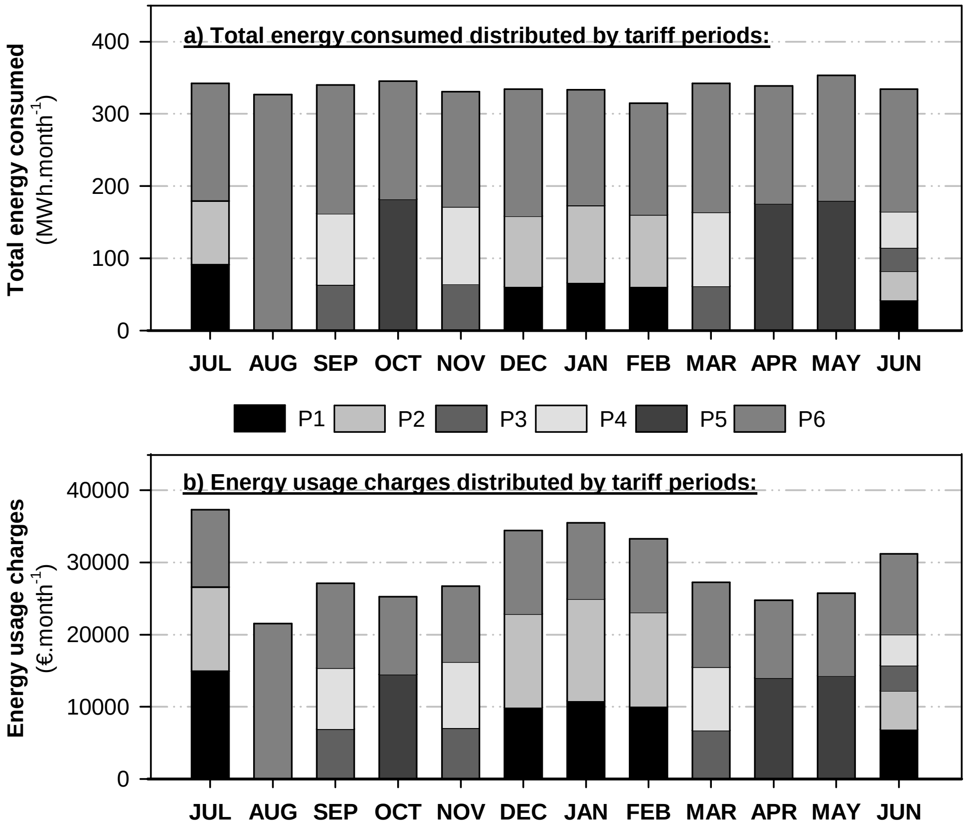

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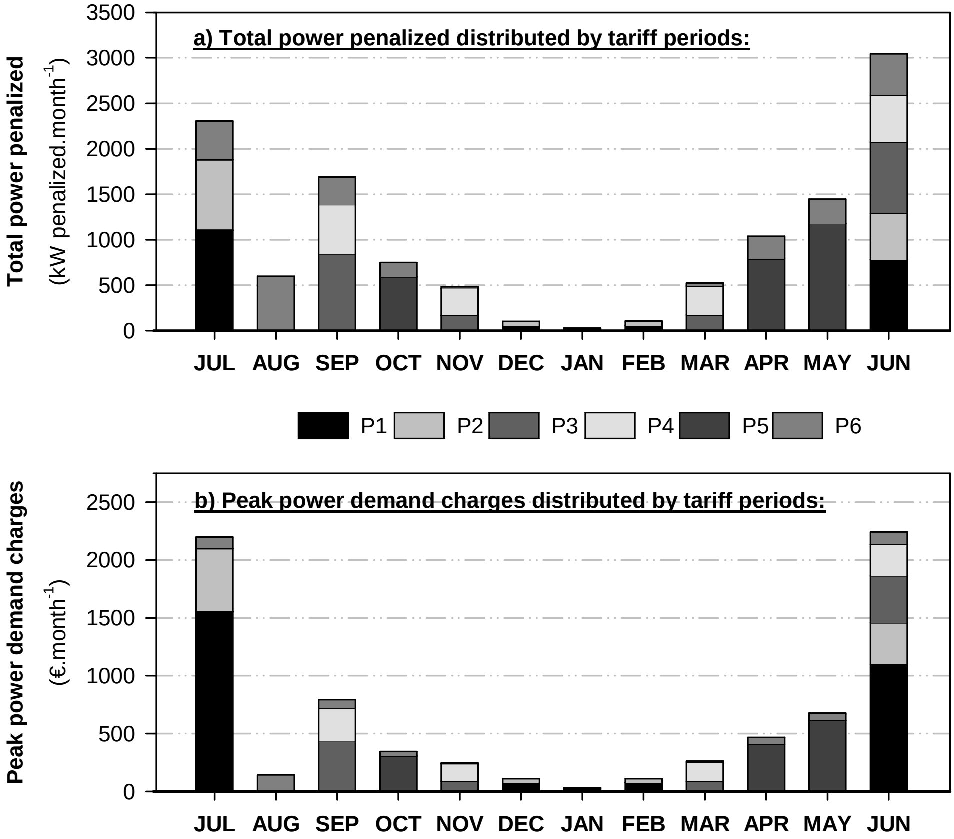

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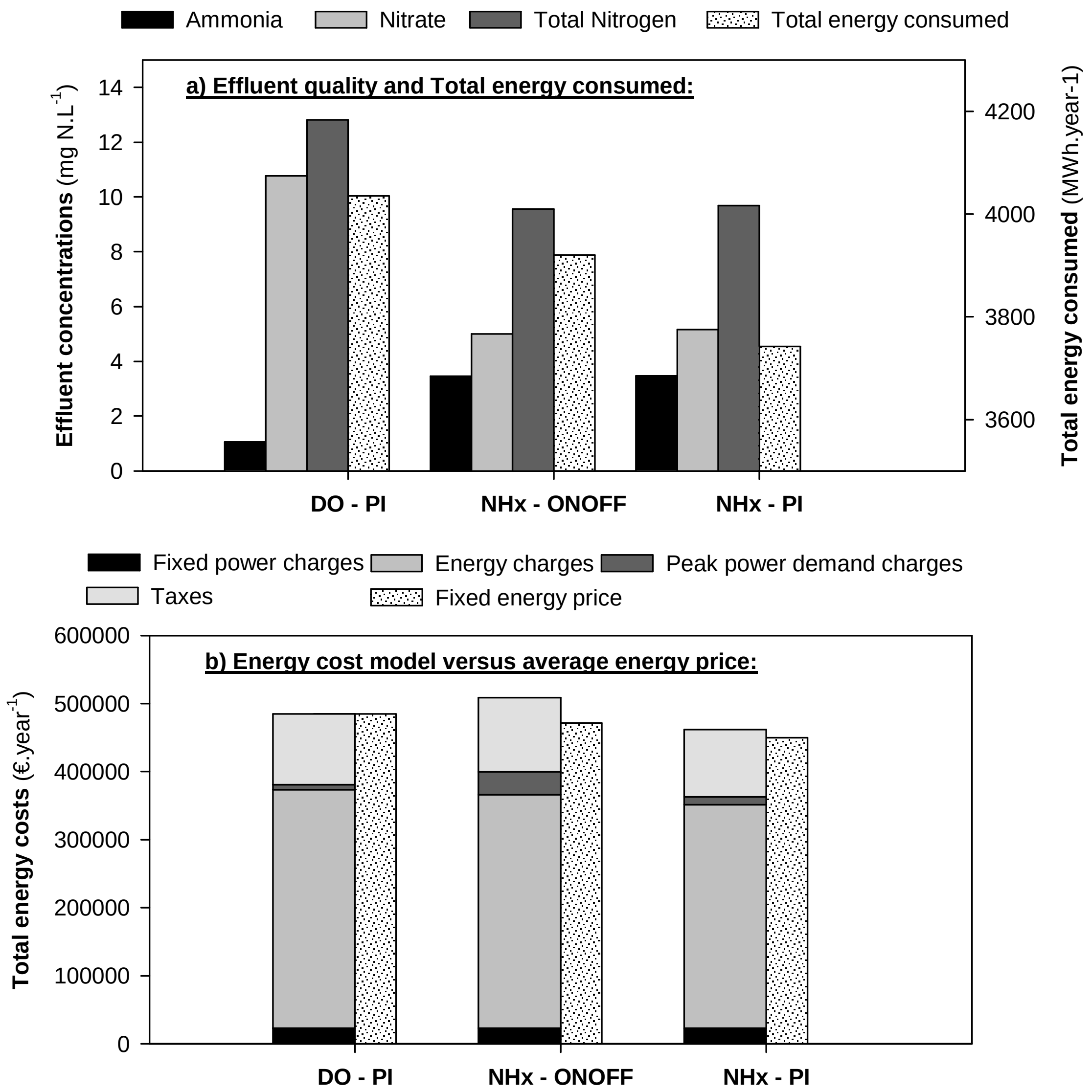

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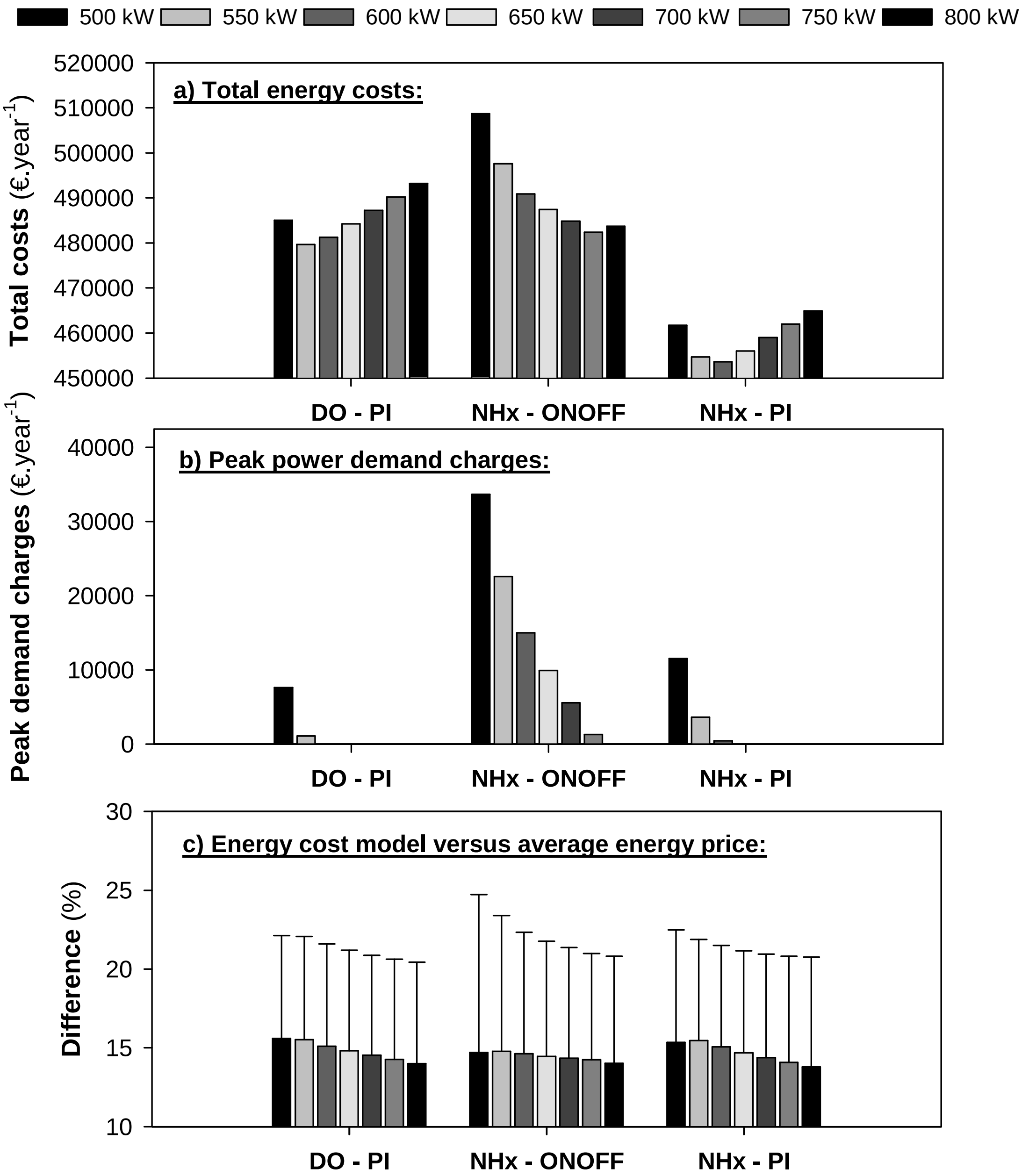

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