Effective dynamic tariffs for price-based Demand Side Management with grid-connected PV systems

Nikolas Philippou*, Maria Hadjipanayi, George Makrides, Venizelos Efthymiou and George E. Georghiou
FOSS Research Centre for Sustainable Energy, Photovoltaic Technology Laboratory
Department of Electrical and Computer Engineering, University of Cyprus
Nicosia, Cyprus
*Nikolas Philippou (phone: +357 22894398, Fax: +357 22895370, nphili01@ucy.ac.cy)

***Abstract*—In isolated electricity networks the penetration of renewable energy sources offers, among others, the advantage of distributed electricity. At the same time, as penetration levels increase, controls and regulations need to be imposed in order to alleviate rising grid integration issues. Some of these can be prevented through the use of dynamic tariffs enabling Demand Side Management. In this work, a new tool for the optimization of dynamic tariffs is developed. This is based on statistical analysis of the consumption profiles and optimization procedures, aiming to derive the most appropriate Time-of-Use (ToU) tariffs. The consumption profile analysis performed on three hundred prosumers in Cyprus showed strong correlation between the measured and the average consumption profiles while the self-consumption rate of existing prosumers is averaged to 30%. The developed dynamic ToU blocks in comparison with the load curve exhibit a mean absolute percentage error and root mean square error of 6.22% and 12.32%, respectively.**

***Index Terms*-- Demand side management, net metering, photovoltaics, time-of-use tariffs.**

I. Introduction

The increasing integration of renewable technologies and particularly grid-connected photovoltaic (PV) systems at the low voltage (LV) network, offers the advantage of distributed electricity generation. However, this does not remedy the problem of intermittency and grid stability issues for cases with weak correlation between the electricity demand and production profile from PV. Grid stability issues that are attributed to renewable energy sources (RES) integration can be mitigated through advanced demand side management (DSM) schemes which aim to levelise peak demands. Along these lines various DSM schemes have already been applied in different countries such as the USA, China and Germany for this purpose [1]–[5]. The main DSM schemes include application of energy storage systems (ESS) and price-based DSM.

Currently, ESS is a popular way to enable DSM for the commercial and domestic sector and is used in order to levelise and shape consumption profiles. At communal scale DSM can further be achieved with the application of Plug-in Electric Vehicles (PEV) and smart algorithms that control the bi-directional energy flow (grid-vehicle and vehicle-grid) at the distribution level.

Alternatively, price-based DSM can be used at domestic and commercial levels and can provide benefits to both grid utilities and consumers. In particular, through price-based DSM, utilities are able to better utilize the grid and to reduce the operating and maintenance costs because of the levelised consumption. Furthermore, this offers the advantage to consumers of lower electricity bills at different time periods.

In this work, the methodology followed to develop a dynamic tariff tool is outlined, in the scope of achieving optimum dynamic tariffs and thus improved DSM. In particular, the implementation of the dynamic price-based DSM tool was accomplished from the extensive analysis of consumption profiles, electricity production of 3 kWp PV systems, billing periods, tariff rates and compensation of collected renewable energy credits (REC) for a large amount of households in Cyprus [6]. Furthermore, the self-consumption rate and the correlation between average consumption profiles, from an average 400,000 domestic consumers as obtained from the Electricity Authority of Cyprus (EAC), and the measured profiles of three hundred prosumers in Cyprus was derived for the winter season. Subsequently, a preliminary dynamic tariff tool was implemented in this work, in the scope of optimizing the self-consumption rate of households based on DSM schemes.

II. Background Theory

Price-based DSM programs offer an alternative to the traditional flat tariffs and comprise of Critical Peak Pricing (CPP), Real-Time Pricing (RTP) and Time-of-Use (ToU) tariffs [7], [8]. Amongst the different schemes, ToU tariffs are commonly preferred because the price of energy consumption is fixed for different periods of the day in contrast to other price-based DSM programs where the price fluctuates following the real time cost of electricity [7], [8]. In addition, consumers and utilities have the advantage of risk-averse attitude to price uncertainties due to mainly fuel

The project is co-financed by the program LIFE (LIFE+ Environment Policy and Governance) of the European Union under the grant agreement number LIFE 12/ENV/CY/000276.

price adjustments. In this respect, most residential consumers need to upgrade their appliances with automated smart controllers to defer their operation during high prices [7], [9], [10].

The development of an efficient DSM system offers the advantage of generation cost reductions for grid utilities and the increase of operational efficiency. In effect, fewer balancing issues are expected to arise and thus lower transmission and distribution (T&D) investments are required. However, in order to achieve a balanced DSM scheme the existing flat tariffs need to be transformed to ToU tariffs, in order to provide the necessary monetary incentives for domestic consumers to invest in smart appliances for effectively managing their loads. Another important consideration is the prospect of providing consumers the opportunity to have a dynamic role in energy generation and also allowing self-evaluation of daily energy habits. In this way, consumers become also producers, collectively defined as “pro-sumers” (producers-consumers), who contribute to the energy mix and at the same time reduce their consumption by a fair amount through smart energy management.

Even though, ToU tariff schemes offer the advantage of price certainty, the effectiveness of such tariff schemes must be verified prior to implementation because of the eminent high risk of a new peak appearing through load shifts at cheaper price periods, posing negative effects on the optimal operation of the system [1], [11]–[14].

III. Prosumer Features

In support of this work, three hundred prosumers in Cyprus have been selected through the implementation of the SmartPV project (http://www.smartpvproject.eu/), in order to acquire real-life information of the consumption and production profiles and to identify the potential problems and limitations of the existing energy policy. All participating prosumers are geographically spread in Cyprus, in order to cover different socio-geographical situations, with 2/3 of prosumers residing in urban areas and 1/3 in rural areas. In addition, prosumers were selected based on their total yearly electricity consumption (in kWh) in relation to a typical energy production from a 3 kWp grid-connected PV system as applies with the existing net-metering scheme for households in Cyprus.

In addition, the prosumers can monitor their energy habits with the use of different monitoring devices. For 100 prosumers In-House Displays (IHDs) were installed at their households, while others have access either to a web application or receive information about their energy habits through the traditional bi-monthly mail bill. This enables in-depth examination of the prosumer energy behavior changes using different monitoring accessibilities. The provided average consumption profiles of all the prosumers will be examined over a six month period with a traditional flat tariff charge and for a yearly period with price-based DSM.

IV. Methodology

The development of a dynamic ToU tariff tool to enable price-based DSM relies strongly on the analysis of the basic input parameters such as electricity demand and PV electricity production profiles. The correlation between the electricity demand and production profiles forms the basis for the design of the price-based DSM scheme. Consumption and production data acquired from the three hundred prosumers will be used to optimize the dynamic ToU tariff algorithm for the case of Cyprus.

The first step in the development of the algorithm was to identify the maxima and minima for the power consumption periods of the provided average domestic consumption profiles, an approach already implemented and verified elsewhere [15]. The load duration curve of the provided average domestic consumption profile in Cyprus for each season was analyzed in order to identify the inflection points. More specifically, the different inflection points of the curve represent the various load segments which were used in order to obtain the probability density function (PDF) (at a 95 % confidence interval). The PDF of each segment represented the ToU block period for the implemented tool. The dynamic tariff tool developed from the above statistical analysis is capable of deriving the TOU blocks based on the identification of the maximum and minimum consumption segments. The mean absolute percentage error (MAPE) and root mean square error (RMSE) between the TOU block periods and the load curve were 8.65 % and 19.95 %, respectively.

In order to better approach the load curve and minimize the RMSE a more accurate and functional algorithm was developed which is independent of the load duration curves. Optimization methods were used in combination with the statistical results. More specifically, the statistical output ToU block period is used as the initial condition of the optimization procedure which is simulated using Matlab Optimization Toolbox™. In this case, the ToU block is directly compared with the load curve rather than extracting the ToU block from the load duration curve. The objective function of the optimization procedure minimizes the RMSE as described by (1).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(ToUb_k - P_k)^2} \qquad .1$$

where $ToUb_k$ is the derived block period, P_k is the load profile and n is the total sampling interval. Based on this equation, $ToUb_k$ is the variable to be optimized and changes according to the desired levels. To achieve this, the developed optimization tool uses a hybrid optimization function. In particular, simulated annealing [16] and pattern search [17] are the two solvers used to derive the optimum result.

Beyond the identification of the ToU block period, the dynamic ToU tariff tool calculates the electricity bill based on the ToU tariffs set by the user and finds the optimized ToU tariffs based on international practices. The optimized ToU tariffs are calculated using the well-known fmincon solver [18] which finds a constrained minimum of a scalar function of several variables. The computation of the electricity bill is based on the ToU block period, the ToU tariffs and the associated load curve.

Consequently, two different methodologies were followed to derive the final ToU block period: a) combining statistical analysis using the load duration curve and b) optimization methods applied to the load curve.

Finally, the optimized ToU tariffs were computed resulting to the total electricity bill based on the ToU blocks and the corresponding load curve.

V. RESULTS

A. Correlation between the electricity demand and production profiles

The daily electricity production of a typical 3 kWp grid-connected PV system in Cyprus and the average daily consumption profile provided by the grid authority of Cyprus is demonstrated in Fig. 1.

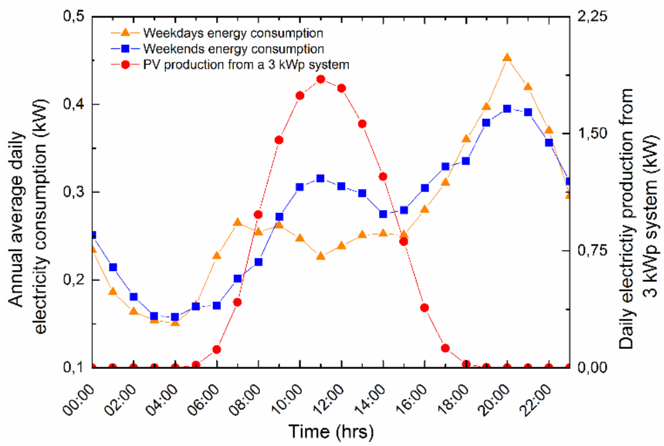

Figure 1. Average daily electricity consumption profile and PV production of 3 kWp PV system, for the winter season in Cyprus.

The plots in Fig. 1 demonstrate that the peak of the PV energy production curve, which is during midday, does not correlate closely with the provided average consumption profile which exhibits a demand peak towards the early evening hours. In this case the correlation coefficient of the two profiles is only 0.18 indicating a poor match between the two.

Another important result extracted from the analysis is that increased PV penetration on the island will be possible once the current demand profile is appropriately shifted and levelised. Consequently, this provides evidence that DSM schemes must be encouraged in order to flatten the electricity demand profile thus, increasing the efficiency of the electricity network and reducing its operational and maintenance costs as well as the overall carbon footprint.

B. Dynamic ToU Tariff tool

A software application tool was developed in order to assist users to visualize the impact on their electricity bill from the different ToU blocks, shown in Fig. 2. Comparison between user input ToU tariffs and optimized ToU tariffs can be done as well as comparison between the electricity bill charged based on flat rate and ToU tariffs.

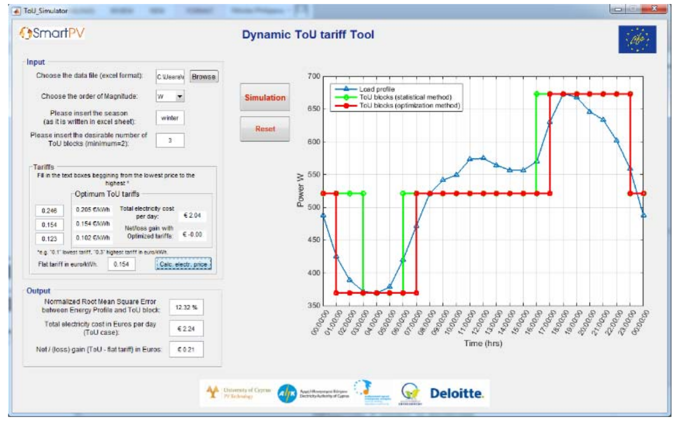

Figure 2. Dynamic ToU tariff software tool.

Fig. 3 depicts the ToU blocks as obtained from the developed dynamic ToU tariff tool for the electricity demand during the winter period (this period refers to the months of December to March). The plots of the ToU blocks were computed by applying statistical analysis performed on the provided average consumption profile and by employing optimization procedures. The MAPE and RMSE between the load curve and the TOU blocks utilizing the optimized tool is reduced by 2.43 % and 7.63 %, respectively, in comparison with the statistical approach, indicating an increased performance and effectiveness. Furthermore, the plots clearly demonstrated that the peak consumption period is charged with the higher tariff, while the lowest tariff occurs during the valley period. Two other periods are further identified during the time intervals 07:00 – 17:00 and 23:00 – 1:00 which represent the transitional period, from the valley to the peak and vice-versa. These time periods are important as they can be used by prosumers to cover their needs that can be shifted from the peak periods but cannot wait until the off-peak period (e.g. cooking, unscheduled devices etc).

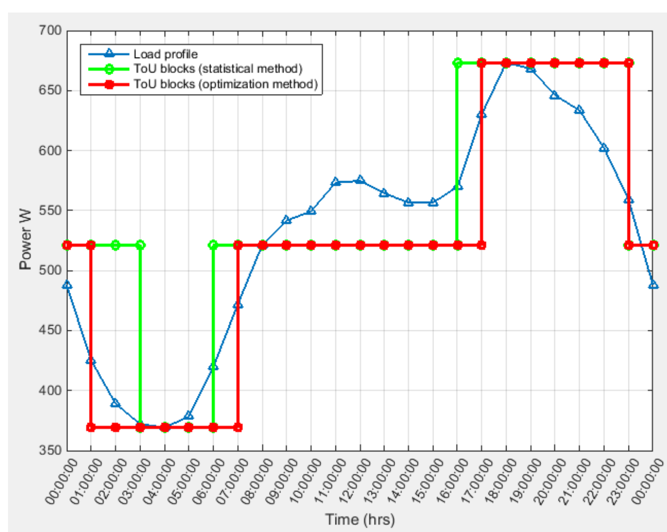

Figure 3. ToU block periods during winter season in Cyprus.

Fig. 4 shows the ToU tariffs and the associated output results computed by taking into account the ToU blocks, ToU tariffs and the load curve. On the left hand side in the

'Tariffs' panel, the user inputs the desired tariffs as he/she considers right. In the 'Optimum ToU tariffs' the optimum tariffs are calculated satisfying certain conditions. These conditions are to keep the middle tariff equal to the flat tariff whereas, the peak tariff to be double than the off-peak tariff. Meanwhile, the difference between the electricity bills charged using flat tariff and Optimum ToU tariffs should be zero if it is assumed that the load profile remains unchanged. From the example illustrated in Fig. 4 it can be observed that utilizing the users' ToU tariffs input the utility will gain € 0.21 per day. On the other hand, the computed optimum ToU tariffs do not affect any of the involved stakeholders since the electricity bill difference between flat charge and ToU charge remains identical.

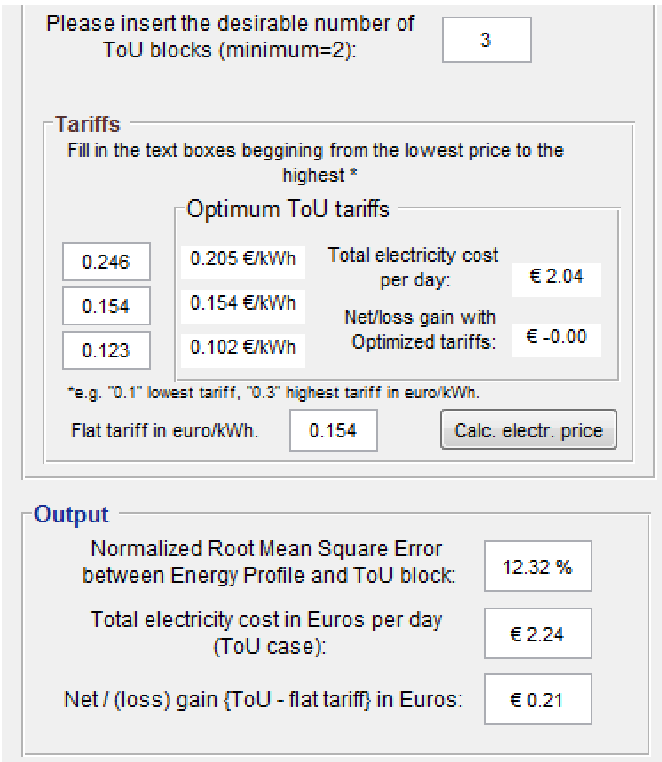

Figure 4. Optimized ToU tariffs maintaining neutral impact on prosumers' electricity bill.

C. *Acquired data from three hundred prosumers*

Data-sets collected during the winter period from three hundred Smart Meters (SMs) which are installed at different prosumers' households in Cyprus, before the application of ToU tariffs, were analysed in order to correlate their consumption profile with the provided average consumption profile. Fig. 5 exhibits the measured data-sets obtained through SMs during this winter and shows an increase of the real consumption of almost 50 % compared to the provided average consumption data-sets. This is so because the historical data were collected from consumers with different economical background as also including cottages. Whereas, the real data-sets are obtained from prosumers who could afford an installation of a PV system and have increased energy needs. However the correlation between the measured and provided average consumption profiles is more than 80 %, showing that the selected prosumers strongly represent the baseline scenario. This consumption behaviour is expected to change with the application of the ToU tariffs.

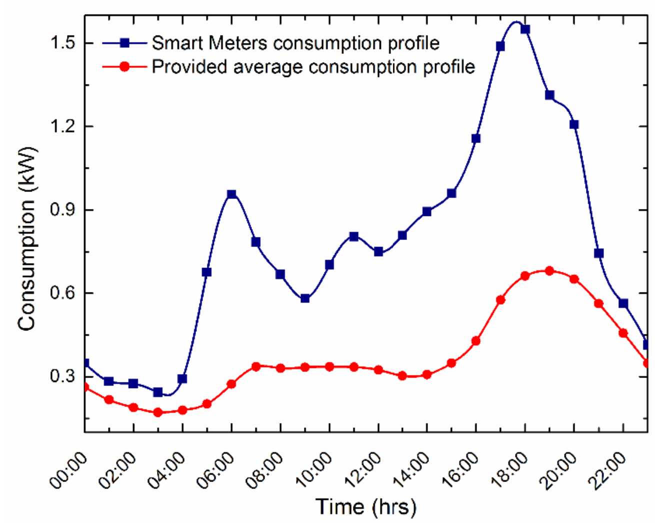

Figure 5. Comparison of household consumption profiles between measured and provided average consumption data-sets.

The self-consumption rate with and without DSM measures was also examined by analysing the current energy profile (without DSM measures) as this is derived from the SMs readings. Fig. 6 exhibits the results of this analysis where the blue, red, orange and yellow line represent the average consumption, the PV production, the export and the import power respectively.

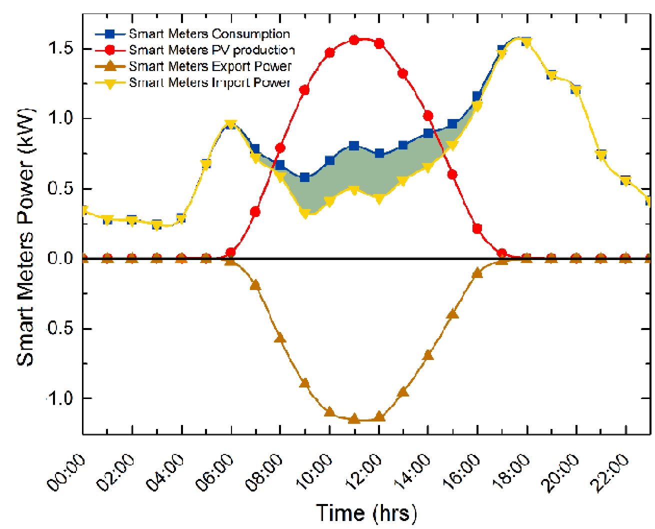

Figure 6. Average prosumer profile obtained through SMs during the winter period.

The calculation of the self-consumption power is implemented using the equations below [19] and the results are presented in Table I.

$$\begin{aligned}\text{Self-consumption} &= \text{total consumption} - \text{import}\\ \text{Self-consumption} &= \text{total PV production} - \text{export}\end{aligned} \tag{2}$$

TABLE I. CALCULATION OF SELF-CONSUMPTION POWER.

Consumption (kW)	19.36
PV production (kW)	10.14
Import (kW)	16.46
Export (kW)	7.24
Self-Consumption (kW)	**2.90**

The average self-consumption power for the participating prosumers is calculated to be 2.90 kW hence, about 28 % of the energy produced is directly consumed on site while the remaining energy is exported to the grid.

VI. CONCLUSIONS

In this work, the need for the development of DSM schemes was initially demonstrated through the comparison of the typical household electricity demand with the electricity generated by a 3 kWp rooftop grid-connected PV system. Subsequently, a new tool for the optimization of dynamic ToU tariffs has been developed based on two different methods, in order to promote effective DSM practices in the electricity network of Cyprus. This is based on statistical analysis of the provided average consumption profiles and optimization procedures, aiming to derive the most appropriate ToU tariffs. The statistical method showed a MAPE and RMSE of 8.22 % and 19.95 %, respectively, by comparing the resulted ToU blocks and load curve. On the other hand, the optimization method resulted a MAPE and RMSE of 6.22 % and 12.32 % respectively, proving the effectiveness and increased accuracy of the optimization method. In addition, energy data-sets have been collected from participating prosumers before the application of the ToU tariffs and comparisons between measured and provided average consumption data was made. The results indicated strong correlation between the two profiles while the average self-consumption rate with the existing net metering scheme is about 28 %. This is a subject to change after the application of the ToU tariffs.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contribution of Electricity Authority of Cyprus (EAC) in this work as part of the SmartPV project.

REFERENCES

[1] J. Torriti, "Price-based demand side management: Assessing the impacts of time-of-use tariffs on residential electricity demand and peak shifting in Northern Italy," *Energy*, vol. 44, no. 1, pp. 576–583, Aug. 2012.

[2] C. Yu, D. Nan, and R. E. N. Yangkai, "Investigation on electric load peak and valley characters and demand response evaluation based on spectral analysis," in *International Conference on Advanced Power System Automation and Protection (APAP)*, 2011, pp. 1258–1262.

[3] J. Schleich and M. Klobasa, "How much shift in demand□? Findings from a field experiment in Germany," in *European Council for an Energy-Efficient Economy (ECEEE Summer Study)*, 2013, pp. 1919–1925.

[4] D. Dallinger, S. Gerda, and M. Wietschel, "Integration of intermittent renewable power supply using grid-connected vehicles – A 2030 case study for California and Germany," *Appl. Energy*, vol. 104, pp. 666–682, Apr. 2013.

[5] S. Emec, M. Kuschke, M. Chemnitz, and K. Strunz, "Potential for demand side management in automotive manufacturing," in *Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013 4th IEEE/PES*, 2013, pp. 1–5.

[6] N. Philippou, V. Efthymiou, M. Hadjipanayi, I. Papageorgiou, C. Zannettis, M. Delenta, C. Karayiannis, M. Ioannidou, C. Themistocleous, E. Loucaidou, X. Valanidou, and T. Mesimeris, "Smart net metering for promotion and cost- efficient grid-integration of PV technology in Cyprus (SmartPV)," in *9th International Conference on Deregulated Electricity Market Issues in South Easrtern Europe*, 2014, p. 6.

[7] M. H. Albadi and E. F. El-Saadany, "A summary of demand response in electricity markets," *Electr. Power Syst. Res.*, vol. 78, no. 11, pp. 1989–1996, Nov. 2008.

[8] B. Severin, M. Jaske, and A. Rosenfeld, "Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets." Center for the Study of Energy Markets, p. 103, 2002.

[9] I. Bob Rasor, SD Myers, "Electric Energy Magazine: The Perfect Storm in Trasformer Maintenance," *Jaguar Media Inc.*, Canada, pp. 34–36, 2012.

[10] A. Jongejan, B. Katzman, T. Leahy, and M. Michelin, "Dynamic Pricing Tariffs for DTE ' s Residential Electricity Customers," MSc thesis, Deprt. Natural Resources and Environment, University of Michigan, 2010.

[11] S. Gottwalt, W. Ketter, C. Block, J. Collins, and C. Weinhardt, "Demand side management—A simulation of household behavior under variable prices," *Energy Policy*, vol. 39, no. 12, pp. 8163–8174, Dec. 2011.

[12] P. Conlon, "Development of Domestic and SME Time of Use Tariff Structures for a Smart Metering Program in Ireland," 2014.

[13] J. Thumim, "Investigating the potential impacts of Time of Use (TOU) tariffs on domestic electricity customers Report to Ofgem," 2014.

[14] C. M. Flath, "An optimization approach for the design of time-of-use rates," in *IECON - 39th Annual Conference of the IEEE Industrial Electronics Society*, 2013, pp. 4727–4732.

[15] Q. Hui-ting and L. Yi-jie, "Research of Peak and Valley Period Partition Approach on Statistics," in *4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, 2011, pp. 1774–1779.

[16] L. Ingber, "Adaptive simulated annealing (ASA): Lessons learned," *Invit. Pap. to a Spec. issue Polish J. Control Cybern. "Simulated Annealing Appl. to Comb. Optim.*, 1995.

[17] T. G. Kolda, R. M. Lewis, and V. Torczon, "A generating set direct search augmented Lagrangian algorithm for optimization with a combination of general and linear constraints," 2006.

[18] R. H. Byrd, J. C. Gilbert, and J. Nocedal, "A trust region method based on interior point techniques for nonlinear programming," *Math. Program.*, vol. 89, pp. 149–185, 2000.

[19] O. Schaefer, S. Willborn, S. Goeke, J. A. Toledo, V. Cassagne, and A. Roesch, "Self Consumption of PV Electricity," EPIA, 2013.