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Abstract

The share of renewable energy in the overall production of electricity has been increasing in recent years. However, there are worries that increase in share of solar and wind power could destabilize the grid owing to their being intermittent resources. We propose an algorithm for Time of Use (ToU) retail pricing for demand-shaping and to achieve higher utilization of green intermittent power plants (RE) in a capacitated market. Our experiments and analytical models identify the conditions that favour implementation of TOU pricing and condition for RE to be profitable.We explore the impact of a Time of Use (TOU) retail pricing in a capacitated and deregulated electricity market that is supplied from a finite mix of intermittent renewable and steady non-renewable resources. Through a set of experiments the TOU retail pricing is compared with fixed retail pricing. Our models and the numerical experiments reinforce the existing literature that increasing share of renewable energy reduces energy prices under both pricing schemes. Our experiments indicate that with increasing share of renewable energy, and demand and supply uncertainties, TOU retail pricing results in higher meeting of demand, higher expected revenues for the energy firms and higher utilization of non-renewable supply. Our experiments also indicate that fall in prices that occurs as a consequence of increasing share of renewable energy is lesser in TOU pricing compared to fixed pricing, which makes it less disadvantageous to existing non-renewable energy suppliers and potential investments in non-renewable energy.

Keywords: Capacitated electricity market, deregulated electricity market, intermittent resources, renewable energy, Time of Use (TOU) retail pricing, uncertain supply, variable demand, fixed tariff retail pricing.

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1. Introduction

Increase in supply from intermittent renewable sources of energy (RE) like solar and wind, has resulted in significant fluctuation in the supply to power grid. With no effective and economical mode of storage for energy, supply-demand matching is of utmost importance for economic and operational efficiency[4]. Excess supply from RE would rendertemporary closure of certain conventional plants (NRE) orwould force NRE to supply at a sub-marginal cost of production[5] or curtailment of renewables (Klinge Jacobsen & Schröder, 2012), a paradox (Blazquez, Fuentes-Bracamontes, Bollino, & Nezamuddin, 2018).This is owing to the merit order effect wherein NRE cater to demand only in excess of RE supply (Woo et al., 2016). While closure of NRE augurs well for the society owing to the reduction in emission, butcurtailment of renewables is highly undesirable both from the economic and the environmental perspective. It is thus, imperative to shift demand to time-slots where excess RE supply is available to maximize the utilization of RE. Shaping demand becomes more important with the rising focus on electric vehicles(Joskow & Wolfram, 2012), wherein the demand for electricity for charging electric vehicles will only rise.

The prevalent tariff mechanisms, like the two-part tariff, fixed tariff (FT) and tiered tariff, although easy to implement, are not very effective.These tariff mechanisms result in cross-subsidization among consumers (consumers having excess peak-demand are cross-subsidized by those who consume less). Real-time pricing (RTP), theoretically an effective tool for demand shaping[Sioshansi & Short (2009), Allcott (2011), Kopsakangas Savolainen & Svento (2012)], is costly to implement and is limited by consumer'sbounded rationality wherein consumers are unable to change demand instantaneously(Chao, 2011). RTP is effective only with automated smart loads, which are expensive;

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[4] Hitchin, P. (2017). Energy demand forecasting in a rapidly changing landscape. Transform, GE Power. Retrieved from:https://www.ge.com/power/transform/article.transform.articles.2017.dec.energy-demand-forecasting-in-a. Accessed on September 19, 2018.

[5] Chestney, N. (2017). Nearly all European coal-fired power plants will be loss-making by 2030 –research. Retrieved from:https://www.reuters.com/article/us-europe-coal/nearly-all-european-coal-fired-power-plants-will-be-loss-making-by-2030-research-idUSKBN1E201Q. Accessed on December 25, 2018.

hence only 3% of the people use RTP effectively[6]. There is a need for a tariff mechanism that provides consumers and producers with adequate time to plan their demand and supply, respectively.

Differential pricing across time is an effective tool in shaping demand (Wolak, 2011). In this paper, we propose a novel time-of-use (TOU) tariff mechanism, announced a month in advance, which takes into consideration demand at hour granularity, since with intermittency of RE "data granularity matters" (Hu, Souza, Ferguson, & Wenbin, 2015). InflexibleNRE (e.g., Coal-based power plants) need to maintain a minimum operating level that sometimes leads to supply at a loss, especially when supply from RE is available in excess. In literature, the minimum operating level of NRE has not found enough emphasis. Our model takes this into account and would enableNREtoreduce their losses by temporarily shutting down plants whenever an excess supply from RE is available which is currently fraught with operational challenges since the power plants are informed of the need to reduce the supply only a few hours in advance (Wang, Mazumdar, Bailey, & Valenzuela, 2007). The proposed TOU tariffs, announced a month in advance,has the potential to influence the customers' consumption pattern and suppliers' production planning effectively.

2. Literature Review

An argument common in much of the literature on electricity markets is the fact that electricity cannot be stored. Hence, supply must equal demand at a given point in time and has been one of the major managerial and technological challenges faced by this industry. Before the arrival of competitive pricing, the electricity sector was considered a natural monopoly where efficient production required a monopoly supplier that was subject to government regulation of prices, entry, investment, service quality and other aspects of firm behavior (Joskow, 1997). The author argues that "traditional regulatory pricing principles based on the prudent investment standard and recovery of investment costs, implicitly allocates most of the market risks associated with investments in generating capacity to consumers rather than producers."

Oum, Oren and Deng (2006) is one of a stream of electricity market literature reporting their transit in the past decade from regulated monopolies to deregulated competitive ones where generation,

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[6] Trabish, Herman.K (2019). What will electricity pricing look like in 2040?. Retrieved from: https://www.utilitydive.com/news/what-will-electricity-pricing-look-like-in-2040/558708/. Accessed on May 12, 2019.

transmission and distribution are no more by the same firm. They state that electricity is now bought and sold in the wholesale market by numerous market participants such as generators, load serving entities (LSEs), and marketers at prices set by supply and demand equilibrium. Pricing has been an important tool in attracting new investments in energy utilities and managing demand in electricity markets. Borenstein (2000) argues in favor of competition instead of regulation in determining prices in wholesale electricity markets. Describing market power as the ability of a firm to increase price and profit by reducing supply, he argues that it should not be confused with competitive peak-load pricing.

However, the market equilibrium through competitive pricing is still pertaining largely to the wholesale markets only. Borenstein and Holland (2005) describe the strong disconnect between retail pricing and wholesale costs in restructured electricity markets, where retail prices remain steady even though wholesale prices fluctuate extremely. They argue that flat-rate retail pricing has the problem of preventing hour-by-hour prices that reflect wholesale costs and fails in a competitive market in maximizing customer welfare. They also argue that increasing the share of customers on real time pricing (RTP) would improve efficiency though it need not reduce capacity investment. Allcott (2011) evaluates a program to expose residential consumers to RTP and found that enrolled households are price elastic.They responded by conserving energy during peak hours but did not increase average consumption during off-peak times. The program increased consumer surplus by $10 per household per year which is one to two percent of the electricity costs. Chao (2010) explores the benefits of demand-response programs that pay consumers to reduce their demand during high-price periods against a baseline, which is the demand had it not been reduced. He discusses the various problems associated with use of an administrative customer baseline that could create adverse incentives and cause inefficient price formation. He identifies fixed uniform retail rate as a barrier to price-responsive demand, which is essential for realizing the benefit of a smart grid. Yang et. al. (2013) report various studies on electricity pricing and report that while some investigated peak pricing considering demand uncertainty only others investigated peak pricing considering supply uncertainty only. They argue that most studies focused on pricing in the peak period only and thereby ignored the possibility of consumption shifts from peak hours to off-peak hours. They propose a time-of-use tariff with consideration of consumer behavior that could create a win-win situation for both the producer and consumers.

Smart Grid and Smart Metering are necessary for the implementation of real-time or time-of-use tariff in retail markets. Blumsack and Fernandez (2012) describe the rapid advent of the smart grid and discuss its potential to act as an enabling technology for renewable energy integration, price-responsive electricity demandand distributed energy production. Allcott (2011) report that though the customer surplus from RTP is meagre compared to the $150 per household investment in retail smart grid applications, many utilities are investing in them as they offer substantial cost savings and provide the option of offering RTP.

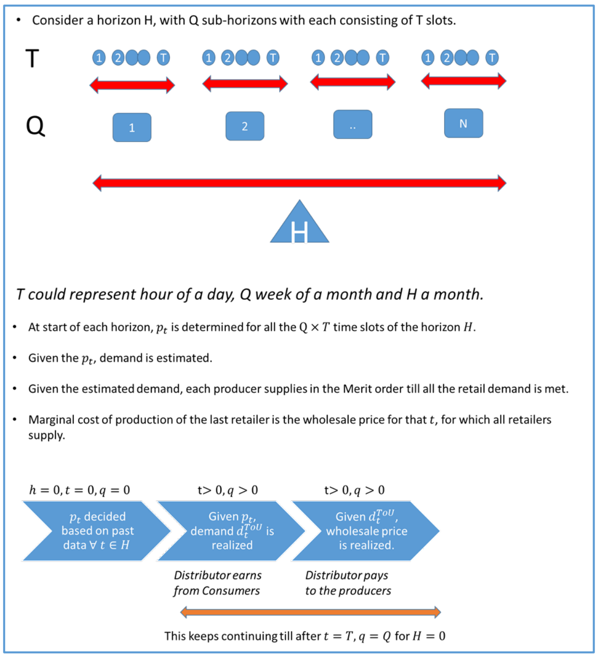
The literature on renewable energy has two streams relevant to our study. The first one is regarding feed-in-tariff (FIT) that is necessary to encourage investment in renewable energy. Frondel et. al. (2010) while critiquing the German renewable energy model argue that "supporting renewable technologies through FITs imposes high costs without any of the alleged positive impacts on emissions reductions, employment, energy security, or technological innovation." Garcia et. al. (2012) argue that neither a FIT nor a renewable portfolio standard are independently capable of inducing the socially optimal level of investment in renewable energy. Couture and Gagnon (2010) describe different ways to structure FITs. These could broadly be categorized into two groups based on whether the remuneration is dependent or not on the electricity price. While the former encourage electricity generation when it is needed most, the latter has the advantage of lowering investment risks. Thus FITs that are dependent on electricity price help in easing peak supply pressures and improves market integration of renewable energy sources. Lesser and Su (2008) argue that a FIT structure should be economically efficient and propose a two-part FIT consisting of a capacity payment and an energy payment that is tied directly to the market price of electricity.

The second stream of literature on renewable energy addresses the issues associated with its being an intermittent resource. Woo et. al. (2011) show that though increasing wind generation could reduce spot prices, it could also increase the spot-price variance. Chao (2011) propose an efficient pricing and investment model for electricity markets with intermittent resources. A contribution of this paper is that both demand and supply are considered to be variable, with the supply uncertainty including the variability from intermittent renewable energy sources. His simulation study, based on this modeling, shows that the introduction of renewable energy and dynamic pricing reduces the average cost of electricity. Ambec and Crampes (2012) analyze the interaction between a reliable source of electricity production and intermittent sources such as wind or solar power. They argue that fixed retail pricing distorts the optimal mix of energy sources and that a large share of renewable energy would be sustainable only with a structural or financial integration of the two types of technology.

Lastly we review some literature on hour-ahead and day-ahead forecasting of renewable energy. Potter et. al. (2009) suggest that the smart grid operations can be considerably improved by accessing information about the likely behavior of renewable energy. Apart from longer-term assessments they highlight the value of hour-ahead and day-ahead forecasts in better management of a grid. Kavasseri and Seetharaman (2009) use fractional-ARIMA or f-ARIMA models to forecast wind speeds with reasonable accuracy one day in advance. Foley et. al. (2012) review different wind power forecasting methods and their performance over different forecast horizons. They report that with wind farm pooling and hour-ahead or day-ahead forecasting it is possible to predict wind energy accurately. Mellit and Pavan (2010) study the 24 hour solar irradiance forecast using artificial neural network and report a high forecast correlation (above 94%) with actual irradiance. Perez et. al. (2013) too report the advances in solar irradiance forecasting.

3. Model

We propose TOU tariff, announced a month in advance, that shifts demand to maximize utilization of RE while ensuring that the distributor is better off under TOU than under FT. The additional profit that distributor earns under TOU is used in deploying technology, like smart meters, for implementing TOU. We compare the TOU pricing with the FT pricing. Figure 1 briefly explains the setting of the model.In this section, we presentanalytical results for a generic setting with n suppliers.At any period t, demand comprises of an elastic and an inelastic component. Pricing signals influence the elastic component of the demand and lead to shaping of the demand. However, we ensure that total demand for a given month under TOU and FT remains the same. For the sake of simplicity, we assume that for



- Consider a horizon H, with Q sub-horizons with each consisting of T slots.

T could represent hour of a day, Q week of a month and H a month.

- At start of each horizon, p_t is determined for all the $Q \times T$ time slots of the horizon H.
- Given the p_t, demand is estimated.
- Given the estimated demand, each producer supplies in the Merit order till all the retail demand is met.
- Marginal cost of production of the last retailer is the wholesale price for that t, for which all retailers supply.

This keeps continuing till after $t = T, q = Q$ for $H = 0$

Figure 1: *Model Preliminaries and decision timeline*

all time-slotselastic component comprises the same proportion (α) of the total demand.Thus,the demand under TOU, $d_t^{TOU} = d_t(1 + \alpha_t)$ where $|\alpha_t| \leq \alpha$, is the shift in demand, can only vary between $d_t(1 - \alpha)$ and $d_t(1 + \alpha)$ where d_t is the demand at time-slot t under FT.We define price elasticity of demand under TOU, b, as the relative change in demand for every unit change in price, such that$d_t^{TOU} = d_t[1 + b(\bar{p} \ - p_t\ )]$, where $\bar{p}$ is the retail price under FT which is normalized to demand weighted average of wholesale price under FT. This in-turn normalizes the distributor's profit (π_D) under FT to zero. We assume that the cost of storing electricity is too high and, hence, is not an option for any of the firms. By the merit order effect, suppliers with a lower marginal cost of production (MC) cater to the demand before the suppliers with higher MC. Wholesale price for any time$t(w_t)$ is the MC of the supplier catering to demand with the highest MC.

Lemma 1.1: *Customer always benefits under TOU, given that the total demand under TOU is the same as under FT. Total consumer savings by migrating to TOU can be represented as*: $CS = \frac{1}{b}\sum_{t=1}^{T} \alpha_t^2$, where $-\alpha \leq \alpha_t \leq \alpha$.

Lemma 1.2: *If the wholesale price* w_t *does not change under TOU, distributor's profit is concave in per unit increase/decrease in the demand.*$\pi_D^{TOU} - \pi_D^{FT} = \pi_D^{TOU} = -\frac{1}{b}\sum_{t=1}^{T} \alpha_t^2 d_t - \sum_{k=1}^{T} w_k \times \alpha_k d_k$.

Under the objective of maximizing the distributor's profit, for per unit increase in demand in the time-slots with lower wholesale price and corresponding decrease from time-slots where the wholesale price is high, distributor's profit would only increase, till it reaches a maximum. Beyond the optimum point, revenue from consumers falls faster than the reduction in the expenditure of the distributor in the wholesale market.

Theorem 1:*The increment (or decrement) needed for each* t *to maximize distributor's profit is the weighted average of the difference in wholesale price at*t *and other time slots.*

$y_t = \frac{b\times d_t\times\sum_{j=1}^{T}(w_j-w_t)\times d_j}{2\times\sum_{j=1}^{T} d_j}$ where, y_t is the change in demand under TOU at t.

Corollary 1.1: *If the wholesale price for a given time-slot*t *is a wholesale price-weighted average of demand, the demand for a given* t*remains unchanged.*

$w_t \rightarrow \frac{\sum_{j=1}^{T} w_j\times d_j}{\sum_{j=1}^{T} d_j} \Rightarrow y_t \rightarrow 0$where, y_t is the change in demand under TOU at t.

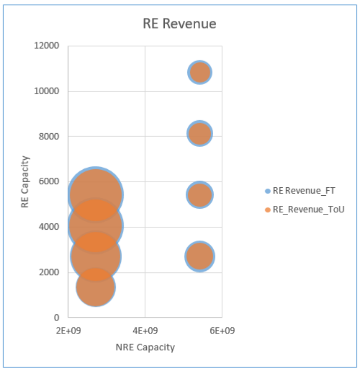
Corollary 1.2: *If the wholesale price does not change for a given* t *under TOU, the demand for a given* t *increases under TOU only when,*$\sum_{j=1}^{T}(m_j \times d_j) > m_t \times \sum_{k=1}^{T} d_k$.

Lemma 1.3: *If an increase in demand increases the wholesale price and ensues reduction in demand where the wholesale price reduces, then the change should be done only if it meets the following criteria:*

$\Delta p - \frac{\sum d_t}{b} - \sum d_t \Delta w_t - \Delta w'_t$where Δp *and* Δw_t is the change in price and wholesale price under TOU as compared to under FT.

4. Results and Discussion

We devise a novel algorithm, based on the lemmas and theorems discussed above, to determine retail prices for each hour a month in advance toshape retail demand. The algorithm maximizes utilization of installed RE such that the distributor, champion for the cause of TOU, earns a positive profit, a complex non-linear problem. We use the algorithm on the actual demand data for electricity. We perform a simulation for stylized values of different parameters like the NRE capacity, RE capacity, minimum operating level of NRE, b, MC of RE and NRE, α. Based on the simulation, we arrive at results that could augur well for a distributor (or a regulator) on decision-making on the implementation of TOU. A few of the results are summarized in figures 2 - 4.Based on these results, we arrive at a decision matrix as shown in tables 1 and 2. While table 1 is aboutthe distributor's decision on implementing TOU, table 2 summarizes the decision that an incoming RE and NRE based firm should take based on the electricity market breakup.As is evident from table 1, the distributor has no incentive in implementing TOU when either both RE and NRE capacity is high or both are low. Since, in such a scenario demand-shaping does not have a substantial impact on the RE utilization, though consumers' savings increase.This is attributed to the fact that under low RE and NRE capacity, the scope for shifting demand to reduce wholesale price is extremely low, while when RE and NRE capacity is very high, the marginal benefit from reducing the wholesale price is outweighed by the resulting decrease in the retail revenue for the distributor. We also find some interesting results from table 2, which also highlights the need for reining in the excessive RE supporting policies by the governments or regulators, lest incessant incoming RE could cause overall loss and shut down of RE plants as is already seen in some parts of the world. Moreover, excessive RE without an appropriate storage technology does not augur well for supply reliability to the consumers.

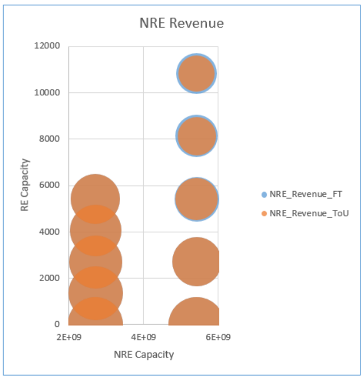


a) Revenue of RE falls as NRE capacity is increased.
   - As NRE capacity increases, need for costlier auxiliary reduces and thus, revenue earned in periods of Zone 3 reduces.

b) For a given demand profile till a threshold value of NRE capacity, RE revenue increases with the rise of RE capacity, beyond which its revenue decreases with rising RE capacity.
   - Till a threshold value of NRE capacity, Auxiliary comes into play owing to demand that transpires Zone 3. In those periods, with an increasing RE capacity total revenue also increases till a limit.
   - However, beyond a threshold value of NRE capacity incoming auxiliary is less and a rise in RE capacity only reduces instances of demand going to zone 2 and thus a reduction in its revenue.

c) With increasing NRE capacity, relative shrinkage of RE revenue under ToU as compared to FT is higher.
   - Owing to reduction in the number of instances in Zone 3.

Figure 2: *Result 1 (RE Revenue with RE and NRE Capacity)*



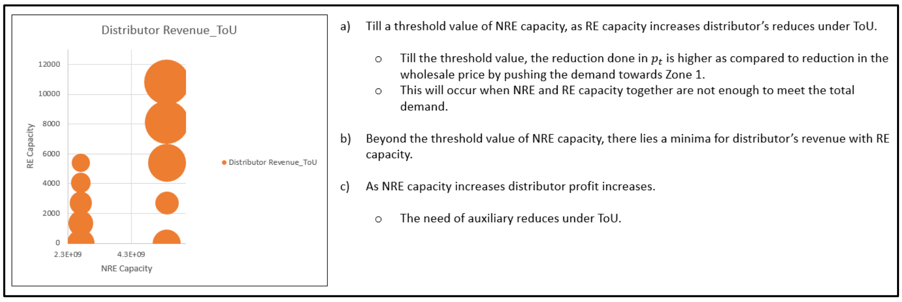
a) Revenue of NRE falls as RE capacity is increased.
   - As RE capacity increases, demand in Zone 3 reduces and thus the decrease in NRE.

b) Till a threshold value of RE capacity, revenue of NRE increases with increasing capacity. However, beyond the threshold its revenue decreases with rising capacity.

c) NRE is worse-off under ToU as compared to FT.

d) With increasing NRE and RE capacity, relative shrinkage of NRE revenue under ToU as compared to FT is higher.

Figure 3: *Result 2 (NRE Revenue with RE and NRE Capacity)*



a) Till a threshold value of NRE capacity, as RE capacity increases distributor's reduces under ToU.
  - Till the threshold value, the reduction done in p_t is higher as compared to reduction in the wholesale price by pushing the demand towards Zone 1.
  - This will occur when NRE and RE capacity together are not enough to meet the total demand.

b) Beyond the threshold value of NRE capacity, there lies a minima for distributor's revenue with RE capacity.

c) As NRE capacity increases distributor profit increases.
  - The need of auxiliary reduces under ToU.

Figure 4: *Result 3 (Distributor revenue with RE and NRE Capacity)*

References

Allcott, H. (2011). Rethinking real-time electricity pricing. *Resource and Energy Economics*, *33*(4), 820–842. https://doi.org/10.1016/j.reseneeco.2011.06.003

Blazquez, J., Fuentes-Bracamontes, R., Bollino, C. A., & Nezamuddin, N. (2018). The renewable energy policy Paradox. *Renewable and Sustainable Energy Reviews*, *82*(April 2017), 1–5. https://doi.org/10.1016/j.rser.2017.09.002

Chao, H. (2011). Efficient pricing and investment in electricity markets with intermittent resources. *Energy Policy*, *39*(7), 3945–3953. https://doi.org/10.1016/j.enpol.2011.01.010

Hu, S., Souza, G. C., Ferguson, M. E., & Wenbin, W. (2015). Capacity investment in renewable energy technology with supply intermittency: Data granularity matters! *Manufacturing and Service Operations Management*, *17*(4), 480–494. https://doi.org/10.1287/msom.2015.0536

Joskow, P. L., & Wolfram, C. D. (2012). Dynamic Pricing of Electricity. *American Economic Review*, *102*(3), 381–385. https://doi.org/10.1257/aer.102.3.381

Klinge Jacobsen, H., & Schröder, S. T. (2012). Curtailment of renewable generation: Economic optimality and incentives. *Energy Policy*, *49*, 663–675. https://doi.org/10.1016/j.enpol.2012.07.004

Kopsakangas Savolainen, M., & Svento, R. (2012). Real-Time Pricing in the Nordic Power markets. *Energy Economics*, *34*(4), 1131–1142. https://doi.org/10.1016/j.eneco.2011.10.006

Sioshansi, R., & Short, W. (2009). Evaluating the Impacts of Real-Time Pricing on the Usage of Wind Generation. *IEEE Transactions on Power Systems*, *24*(2), 516–524. https://doi.org/10.1109/TPWRS.2008.2012184

Wang, L., Mazumdar, M., Bailey, M. D., & Valenzuela, J. (2007). Oligopoly models for market price of electricity under demand uncertainty and unit reliability. *European Journal of Operational Research*, *181*(3), 1309–1321. https://doi.org/10.1016/j.ejor.2005.07.027

Wolak, F. A. (2011). Do residential customers respond to hourly prices? Evidence from a dynamic pricing experiment. *American Economic Review*, *101*(3), 83–87. https://doi.org/10.1257/aer.101.3.83

Woo, C. K., Moore, J., Schneiderman, B., Ho, T., Olson, A., Alagappan, L., … Zarnikau, J. (2016). Merit-order effects of renewable energy and price divergence in California's day-ahead and real-time electricity markets. *Energy Policy*, *92*, 299–312. https://doi.org/10.1016/j.enpol.2016.02.023