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Master's Thesis

Assessment of Menu of Contracts' Incentive Properties under Different Designs of Sharing Factor Functions

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Summary

Incentive regulation has become challenging due to the increased information asymmetries and uncertainties driven by the diffusion of distributed energy resources (DER) and smart grid technologies. A combination of a Reference Network Model (RNM) and a menu of profit-sharing contracts has been used in this thesis to address these problems in electricity distribution. RNM is a tool which can be used by regulator to estimate the investment cost needed by distribution system operators (DSOs) and thus, the problem of information asymmetries between regulator and DSOs can be mitigated.

Menu of contracts, as defined in this thesis, is a regulatory scheme with the revenue determined ex-ante and reviewed ex-post, albeit based on some pre-defined rules. It ensures DSO to receive the greatest reward when the forecast investment cost coincides with the true expenditure in that regulatory period. Therefore, the use of menu of contracts can encourage truth-telling and hence avoid strategic behaviour of DSOs. Consequently, this regulatory mechanism has drawn some attention from regulators as a mean to tackle the aforementioned increasing uncertainties.

The sharing factor is a key parameter that is needed to build a menu of contracts. It determines the strength of the incentive given to the DSO, i.e. how much network companies would benefit from cost reductions or how much they would be penalized for an increase in costs as compared to allowances. In a conventional profit-sharing contract, the sharing factor is a constant value. However, under the menu regulation considered in this thesis, this parameter is obtained as a function of the ex-ante investment cost estimation submitted by the DSO.

Four sharing factor functions have been designed: two functions with a different rate of change when the DSO/regulator ratio increases (increasing and decreasing rate of change respectively) and two functions with an asymmetric sharing factor dependent on whether the difference between actual expenditure and allowed revenue is positive or negative. These sharing factor functions are applied in the menus of contracts, together with the network expansion cost estimated by RNM at different levels of PV penetration to assume different realizations for regulator's forecast cost, DSO's forecast cost and actual expenditure in menu of contracts.

Sharing factor functions with different rate of change across DSO/regulator ratio provide the regulator with higher flexibility in setting incentive strength of the menu. The analyses show that, when the regulator has a high level of confidence with the benchmark cost, a sharing factor function with increasing rate of change when DSO/regulator ratio increases can be particularly useful, and vice versa. While for a sharing factor function which varies with actual expenditure, it is possible for the regulator to reward outperformance and penalize underperformance at a different rate, especially when one outcome is more desirable than the other. In case the regulator wishes to deter overspending over cost-saving, a sharing factor function which increases with the actual expenditure can be used. On the other hand, when the regulator wishes to have the investment projects completed rather than to avoid overspending, a sharing factor function which decreases with actual expenditure can be used.

All in all, these sharing factor functional forms can be used to achieve different requirements desired in the remuneration scheme. Careful tuning of the parameters used in these functions makes the menu of contracts more flexible in term of having different rate of change of sharing factor with DSO's estimated cost and with actual expenditure.

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Chapter 1 Introduction

As the technology develops, electricity consumers find that installing and operating their own electric power is more economical and beneficial. This generation of power at the point of consumption is called the distributed generation (DG). The solar photovoltaic (PV) system is one of the example of DG which converts sunlight into electricity that is gaining more and more popularity among consumers. As the network infrastructure must be able to meet the peak demand requirement, there will be infrastructure which is underutilized during non-peak demand period. DG can be used to provide power to the grid during peak demand period, hence reducing the capacity requirements and new generation utility (Mateo, et al., 2016). Instead of just having the electricity supply from central generator to the end consumers, the consumers can now generate their own electricity and even supply them to the grids, thus introducing changes to the operation of distribution system. In brief, the emerging technology introduces changes to the existing network system and urge the necessary adaptions in the system (Cossent & Gómez, 2013).

Distribution system operators (DSOs) need to make significant investments in order to adapt these changes and take advantages from the technology. Their responsibility is to manage the distribution networks and ensure the development of an efficient electricity system. They are required to plan and develop their networks so as to accommodate the potential increase in demand and ensure reliability of electricity supply to all consumers. As the DG penetration is growing, it is the DSOs' responsibility to provide distribution grids for connections of DG units. A better distribution grid can promise a more efficient and greater deployment of DG, which enables the maximization of the values of DG, to both the owners and consumers. In the meantime, distribution of electricity is a regulated activity and the regulation is promoting cost reduction from DSOs. Hence, more innovative regulatory approaches are required to accommodate the growing DG penetration and to adopt smarter distribution grids (Cossent, et al., 2010).

However, there are information asymmetries between regulator and DSOs, which make it hard for the regulator to estimate the investment cost needed by the DSOs. The firms know more about the cost of utility and the possible cost reduction opportunities than the regulator. In addition to that, the uncertainty about the future technology development and its cost introduces more challenges. Hence, the firms might show strategic behaviour to take advantage over the information they have and to increase profit. These have become the challenges to incentive regulation. In face of this situation, a regulatory scheme that can effectively incentivize the DSOs is necessary, so that they can optimize the incorporation of DG into the system, to find the most cost-efficient and reliable way to supply electricity (Crouch, 2006).

If the incentives for DSOs are determined ex-ante solely, there will be higher incentives for the firms to improve their efficiency and to cut down on cost. However, there is also a downside for this as there might be gaming behaviour in the DSOs by overestimating the investment costs because there is information asymmetry between DSOs and regulator. In addition to that, the uncertainties of the impact of DG penetrations and technology on the investment cost make the cost estimation at the beginning of regulatory period challenging. On the other hand, incentives for DSOs which are determined ex-post solely can assure the recovery of investment cost. However, the firms might be discouraged from pursuing efficiency in integrating DG into the systems and reducing cost. An effective and consistent remuneration scheme which is able to cope with these uncertainties is needed. In order to achieve a balance between these two extremes, menu of contracts, which is a regulatory scheme with the revenue determined ex-ante and reviewed ex-post had been suggested and it is found to be advantageous (Cossent & Gómez, 2013).

The menu of contracts is designed with a number of components that are carefully calculated in order to make it incentive compatible, which means, the firms will receive the greatest reward when the chosen contract represents their true expenditure in that regulatory period. This scheme offers the DSOs with a range of contracts with different level of incentive. The DSOs can choose the contract which best represents their real estimated investment cost for that regulatory period. The contract is chosen based on the ratio of DSOs' estimated expenditure to the benchmark set by regulator. The allowed expenditure, sharing factor for cost deviation and additional income are determined from the contract chosen ex-ante to ensure incentive compatibility. Since the highest possible reward can only be obtained when the estimated expenditure coincide with the actual expenditure, DSOs are encouraged to reveal the accurate investment forecast (Cossent & Gómez, 2013), (Crouch, 2006).

As there are uncertainties about network uses and emerging technologies, there might be significant actual cost deviation from the ex-ante estimate. This deviation is resulted by possible forecast error and benchmark error. The forecast error might arise due to rapid DG penetration which result in higher network investment. It is also possible that new technologies emergence result in higher saving in network deployment, which is a cause of benchmark error by regulator (Jenkins & Pérez-Arriaga, 2014). Hence, ex-post regulatory review and correction to the remuneration are needed to overcome these errors.

The objective of this thesis is to assess the incentive properties of different designs of menu of contracts during network investment. The variation in their properties is achieved through the use of sharing factor functions with different designs in menu of contracts. In order to assess how the alternative designs performed, RNM is used as a tool to estimate the network expansion cost needed by DSOs during varying PV penetration levels. The resulted costs generated from RNM at different levels of PV penetration are incorporated into the menu of contracts. The outcomes obtained under several scenarios are compared and analysed. The analyses of outcome from this combination will show the practicalities of the menu of contracts that have been designed.

The thesis is organized as followed. In Chapter 2, literature review regarding this topic and the general framework that will be used in this thesis is provided. Chapter 3 is about the methodologies used in the assessment, which are menu of contracts and RNM. Detailed description about the significances of parameters used in menu of contracts and the procedure in applying RNM are presented. Chapter 4 shows the procedure to compute the parameters needed to construct a menu of contracts. Computation of four sharing factor functions with different shapes and their corresponding additional income are provided. The data used when applying RNM method and the output obtained are presented in Chapter 5. Chapter 6 provides the analyses by inputting RNM result into all the menus of contracts designed. Analyses are done by assuming a few scenarios, including DSO's ex-ante cost inflation, actual expenditure lower than forecast and actual expenditure higher than forecast. The outcomes of these menus of contracts are compared to that of a reference menu of contracts. Chapter 7 provides the discussion and conclusion.

Chapter 2 Literature Review and General Framework

The menu of contracts regulatory scheme has been used by the Office of Gas and Electricity Markets (Ofgem) and The Water Services Regulation Authority (Ofwat) in UK and it was proven to be advantageous (Cossent & Gómez, 2013), (Crouch, 2006). In addition to that, this scheme is also used during the rollout of the second generation of smart metering system in Italy. This has further showed the practicality of this remuneration scheme in regulation.

(Crouch, 2006) had discussed about the menu regulation which had been applied in electricity network regulation in the UK which makes CAPEX allowances always incentive compatible and the practicalities of this regulation. Some of the short-comings of RPI-X had also been discussed, for example, there is reducing incentive of cost reduction towards the end of the regulatory period while at the same time, cost reduction should ensure the long-term reliability of output delivery to consumers. As there are uncertainties about the future and information asymmetry between regulator and firms, the regulator is not able to estimate the CAPEX accurately. RPI-X is not able to fully address these concerns. Thus, in order to encourage economic investment in establishing reliable networks, an incentive compatible framework is suggested as it can address the problems of the previous approach and in addition to that, allow the firms to choose the allowance scheme they want.

(Cossent & Gómez, 2013) gave a detailed description on how the menu regulation works from the beginning until the end of the regulatory period, from the submission and correction of the DSOs' investment plan to the construction of menu matrix. A set of equations was derived to allow the regulator to construct menu of contracts in a simpler and clearer way. The paper also discussed the role of parameters involved in these equations and their implications in the menu matrix. The steps involved in constructing the menu of contracts are basically similar to the one described in (Crouch, 2006) by calculating the allowed revenue, sharing factor and additional income. However, instead of using iterative process to ensure incentive compatibility of the menu as in (Crouch, 2006), first order derivative of reward equation was applied to get the function of additional income which ensures maximization of incentive whenever the actual expenditure coincides with the investment forecast, hence achieving incentive compatibility.

Sharing factor or efficient incentive rate is the function which the regulator can use to adjust the strength of incentive given to firms. The regulator rewards outperformance or penalizes underperformance based on this function. In (Crouch, 2006), (Cossent & Gómez, 2013) and (Oxera, 2007), the sharing factor had been defined as linear function of firm's estimated investment cost to baseline ratio with negative slope. The gradient of the slope can be set to control the rate of change of sharing factor with the firm's estimated investment cost to baseline ratio (DSO/regulator ratio). As the magnitude of efficient incentive rate decreases with ratio, the firms with higher estimated cost in relation to baseline will receive smaller reward for outperforming. The companies with higher capabilities to reduce cost will choose the incentive scheme with higher power or vice versa.

Instead of having sharing factor function with constant rate of change, sharing factor function which have different rate of change when the DSO/regulator ratio gets higher can be designed in order to achieve higher flexibility in incentive strength across the DSO/regulator ratio. In the previous design, sharing factor is always the constant with the same DSO/regulator ratio, regardless of the actual expenditure. Cost saving or cost overrun are subject to the same sharing rate. Asymmetry sharing factor function which changes with actual expenditure can be designed so that the regulator can reward outperformance and penalize underperformance at different rate. Asymmetry sharing factor function can be a good practice especially when one outcome is more desirable than the other (Cambridge Economic Policy Associates Ltd, 2012).

In this thesis, menus of contracts are designed using sharing factor functions with different variation across DSO/regulator ratio. In order to analyse the properties of these menus of contracts, the costs of network expansion assuming different levels of PV penetration in the future have been applied. The expected expenditures of network expansions are obtained through the application of a large-scale network planning model, RNM in two real distribution areas. The two distribution areas studied are actual areas with distinct characteristics, which are a densely populated urban area and a rural area with sparse population. The outputs from the brownfield reinforcements in RNM are fed into the menus of contracts. The combination of RNM and menu of contracts can help to address information asymmetry further as regulator can get the network estimated network cost from RNM.

Chapter 3 Methodologies

This chapter presents the methodologies that have been used to assess the incentive properties for DSOs with increasing penetration of PV. There are three sections in this chapter. The first section presents about the menu of contracts. In the menu of contracts, several parameters are needed to compute the incentive for DSOs. The significances of all parameters used in the menu of contracts, including baseline cost, forecast cost, allowed revenue, sharing factor and additional income will be provided. The second section discusses the RNM models which are used to estimate the investment cost needed for different levels of PV penetration. The procedures of greenfield and brownfield reference network generations will be included. The third section provides a clearer view about how menu of contracts is combined with the results of RNM in the analyses.

3.1 Menu of Contracts

Menu of contracts is a combination of ex-ante revenue allowance and ex-post remuneration correction in order to make the final rewards of DSOs to be incentive compatible, which is, ensuring maximum profit when the actual expenditure of firm matches its ex-ante estimation. This characteristic of menu of contracts enables it to address the problem of information asymmetries and cope with strategic behaviour of DSOs by eliminating the incentive of cost inflation. The menu of contracts provides the firms a range of incentive options with different properties and power, from which they can choose according to the incentive and their abilities for cost reduction. The main parameters included in the menu of contracts are allowed revenue, sharing factor and additional income. These parameters are calculated as a function of firms' estimated cost to the baseline cost ratio.

Baseline cost is the benchmark expenditure given by the regulator in the beginning and the firms are required to submit their own estimated investment cost. A ratio is obtained by dividing DSOs' estimated cost with regulator's forecasted cost (DSO/regulator ratio). The incentive properties chosen by the firms for that regulatory period depends on this ratio because all the other parameters in the matrix are determined as functions of this ratio.

The forecasted cost is converted to allowed revenue with specific weightages given to the regulator's baseline cost and DSO's estimated cost. By doing so, the investment cost estimated by DSO is also taken into consideration when determining the allowed revenue. The weightages show the confidence level of the regulator towards the benchmark expenditure. The deviation of actual expenditure from allowed revenue will determine the total reward or penalty given to the firm by the end of the regulatory period (Cossent & Gómez, 2013).

Sharing factor is the proportion of amount that the DSO needs to bear in relation to the deviation of actual expenditure from estimated cost. It is a function which decreases with increasing DSO/regulator ratio and it spreads the profits and risks effectively between DSOs and consumers (Jenkins & Pérez-Arriaga, 2015). The firms can be incentivized for its efficiency, at the same time, the firms also have the risk of bearing part of the cost in case of overspending. The regulator can tune the sharing factor function to adjust its flexibility and variability of the profits. For the firms with low uncertainty about future investment, it is more advantageous to choose a contract with higher sharing factor while contract with lower sharing factor is better for firms with high level of uncertainty (Jenkins & Pérez-Arriaga, 2014). In short, the sharing factor can stimulate the firms' managerial effort to outperform and avoid excessive overspending.

Additional income is also a function of DSO/regulator ratio. It is the extra term added to the reward function in order to make sure that the menu is incentive-compatible. Thus, additional income is a function which makes the final reward to be maximum whenever the true expenditure coincides with the estimated cost. The firms are encouraged to provide the accurate estimated investment cost and hence it can overcome the problem of information asymmetry between regulator and DSOs.

In this thesis, menus of contracts are calculated based on several designs of sharing factor functions and their corresponding additional income functions which make the menu of contracts to be incentive compatible. The four sharing factor functions that have been designed are, two functions with different rate of change when DSO/regulator ratio increases (increasing and decreasing rate of change respectively) and two functions which vary with the difference between actual expenditure and allowed revenue. The functions with different rate of change with DSO/regulator ratio are designed by using linear piecewise, quadratic and cubic functions. By tuning the coefficients of these functions, the degree of rate of change and direction of rate of change can be adjusted. The sharing factor functions which vary with actual expenditure are designed based on a linear sharing factor function. An additional term which changes linearly with the difference between actual expenditure and allowed revenue is added to that linear function so that the sharing factor increases or decreases according to the actual expenditure. By applying these sharing factor functions, menus of contracts show different characteristics. These characteristics and their implications will be analysed further.

3.2 Reference Network Model

RNM can build a large-scale distribution network that connects the end consumers of electricity to the supply points, using their exact GPS coordinates and taking into account different voltage levels, characteristics of network elements, geographical location, technical constraints etc. With all the related information provided to the model, RNM can compute the necessary distribution network investment cost. This model is used by the regulators as a tool to estimate investment cost and to assess the effect of adapting DG into the network (Mateo, n.d.). The two types of reference network model used are greenfield model and brownfield model. In a greenfield model, reference network is built from scratch without considering any existing network. While for a brownfield model, an initial network, either a greenfield reference network or existing real network, is used as the starting point to simulate the cost of necessary network reinforcements for new loads or DG (Mateo, n.d.).

In this thesis, a greenfield reference network is used as the initial network of brownfield model to compute the investment cost needed at different PV penetration level. First of all, areas of interest and their characteristics are identified. Two suitable distribution areas are selected, one from urban and the other one from rural to represent the distribution areas with distinct population density. The urban area is chosen from Madrid city, which is a densely populated area of about 4 km^2 with more than 117,000 residents. While for the rural area, a region of 40 km^2 with about 24,000 residents at the northwest of Madrid is chosen. Actual street maps are used so that the reference networks generated resemble actual networks. The actual street maps used can be found in Appendix A.

Then, the street maps of the areas chosen are converted through image processing into LV and MV electricity consumers with their respective GPS location and power needed. The data about consumers obtained from image processing are being fed into the greenfield model to generate a distribution network. In addition to that, extensive input data and specifications, such as simultaneity factor of consumers, characteristics of network elements, technical parameters and constraints, infrastructure and maintenance cost, and others, are also needed so that the reference networks comply with the actual network as much as possible. This can ensure the quality and reliability of the reference networks. Through this step, the basic reference networks which are optimally adapted to the demand are generated. Figure 1 illustrates the sequence of the whole process involved in building a greenfield reference network, starting from the actual street map, until the grid is planned.

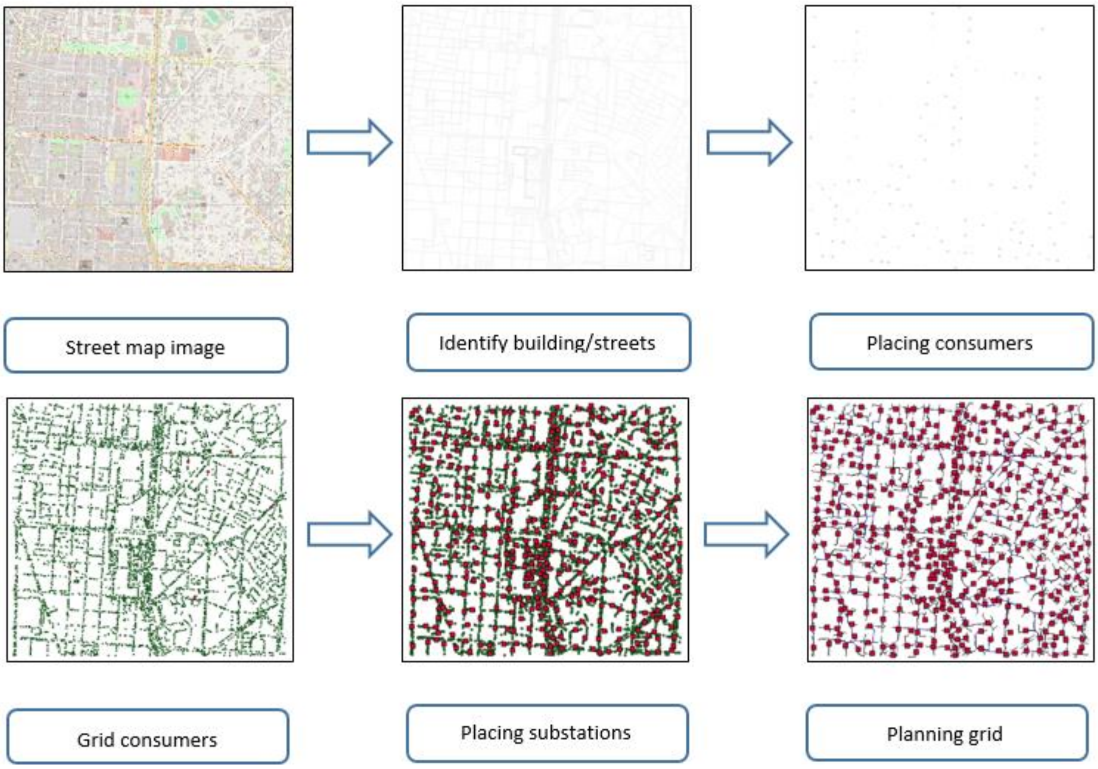

Figure 1 Process in building a greenfield network

After that, the optimal networks reinforcements which can accommodate the network changes in relation to basic scenario are computed by using brownfield model. The greenfield reference networks that have been generated act as the basis to generate brownfield reference networks by assuming a number of scenarios with different levels of PV penetration into the distribution networks. In all the scenarios, the PV panels are located in the existing load points that have been generated through image processing and the output of each PV panels are set to between 2 to 7 kW. Two snapshots are used in each scenario, which are during peak generation and peak demand period. The hourly standard load profiles of Spain in 2016 (Red Eléctrica de España, 2017) are used to determine the peak generation and peak demand periods, which have been identified as from hour 12 to 14 and from hour 20 to 22. These standard load profiles are included in Appendix B. The LV consumers are assimilated to the tariff category 2.0 while MV consumers are assimilated to tariff category 3.1. After all the parameters are determined, brownfield model is used to generate the new distribution network to obtain the estimated investment cost for the diverse set of potential scenarios in the future. The objective function of the model calculates the minimum investment cost and the present value of maintenance cost and energy losses throughout the regulatory period (Fernández, et al., 2010).

3.3 Combination of Menu of Contracts and RNM

The resulted investment costs at different levels of PV penetration generated from RNM are used to assume different realization for regulator's forecast, DSO's forecast and actual expenditure in the menu of contracts. The menus of contracts are constructed using the different designs of sharing factor. The menus of contracts which combine the investment cost from RNM and different sharing factor functions will be compared to a reference menu of contract and the properties shown will be analysed. Figure 2 provides a clearer view about how the assessment in this thesis is done.

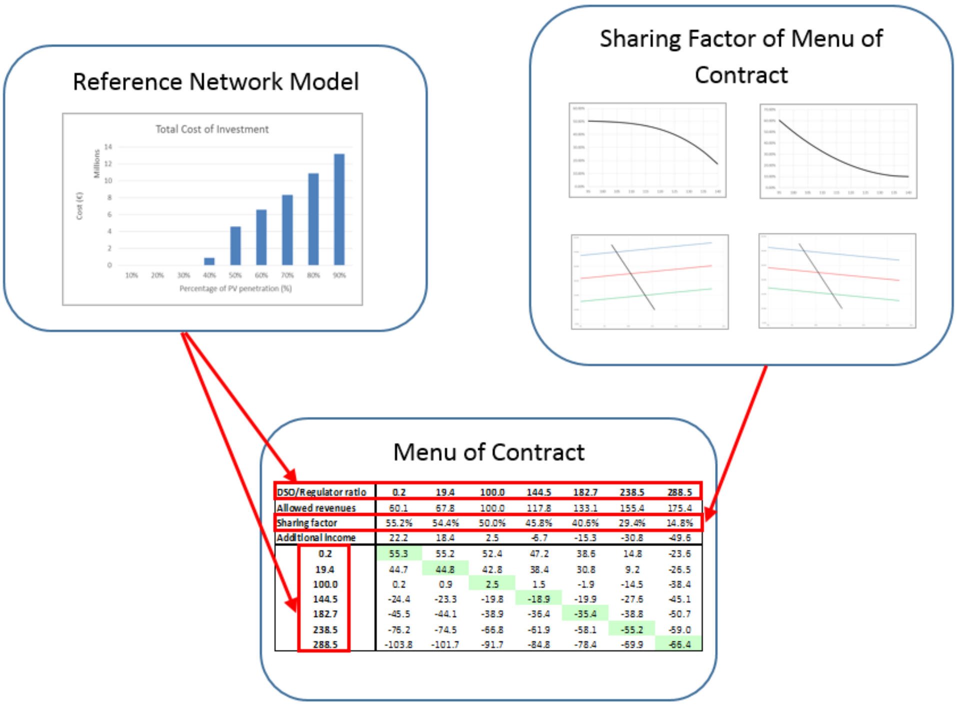

Figure 2 Assessment methodologies

Chapter 4 Menu of Contract

The computations of the menu of contracts are based on the analysis in (Cossent & Gómez, 2013) and (Oxera, 2007). After obtaining the DSO/regulator ratio, there are three parameters which need to be set by the regulator for all levels of DSO/regulator ratio, they are: allowed revenue, sharing factor (SF) and additional income. This chapter consists of four sections, one for each parameters and a summary section in the end. An equation which is used to calculate allowed revenue will be provided in the first section and the same equation will be used all menu of contracts. Second section comprises SF with four different shapes which are designed with several functional forms, including concave down (piecewise linear, quadratic and cubic function), concave up (piecewise linear and quadratic function), linear upward asymmetry and linear downward asymmetry. This section discusses the equations used to derive each SF functions and the procedure of derivation. In the third section, four additional income functions will be derived corresponds to each SF functional forms, which are piecewise linear, quadratic, cubic and linear asymmetry functions. In the last section, a table is drawn to summarize the functions that have been used in each parameters and their significances.

4.1 Allowed Revenue

The ex-ante allowed revenue (AR) is determined by summing the weighted cost estimated by firms and regulator, as in (Cossent & Gómez, 2013)

$$AR = w \cdot 100 + (1 - w) \cdot R$$

where

AR = allowed revenue

R = DSO/regulator ratio

w = weight given to the cost estimated by regulator

4.2 Sharing Factor

SF is the parameter which regulator can adjust to define the strength of incentive given to firms. In (Cossent & Gómez, 2013) and (Oxera, 2007), the SF had been defined as a linear function of DSO/regulator ratio with negative slope. The regulator rewards outperformance or penalize underperformance based on this SF. As the magnitude of SF decreases with ratio, the firms with higher estimated cost in relation to baseline will receive smaller reward for outperforming.

SF functions with increasing rate of change and decreasing rate of change along DSO/regulator ratio have been designed. The aim is to analyse the impact of SF slope's changing rate on the reward function when DSO submits their forecast differently. In addition to that, asymmetry SF functions which vary with actual expenditure have also been designed. The effect of asymmetry SF functions on reward under the same DSO/regulator ratio are analysed to study how asymmetry SF will influence DSOs' spending behaviour once the ex-ante DSO/regulator ratio is fixed. Table 1 summarizes the main characteristics of the SF functions designed and the functional forms used.

Design	Concavity	Symmetricity	SF functional form
1.1	Down	Symmetry	Piecewise linear
1.2	Down	Symmetry	Quadratic
1.3	Down	Symmetry	Cubic
2.1	Up	Symmetry	Piecewise linear
2.2	Up	Symmetry	Quadratic
3	–	Asymmetry	Linear

Table 1 Designs of SF function

4.2.1 Concave Down Sharing Factor Function

Piecewise Linear Function

The SF is calculated by using piecewise linear function with increasingly steeper downward slope when R increases. This is done by joining a few linear functions together. With a known curve, its piecewise linear function can be approximated by plotting points on the curve and joining these points with straight lines. The slope in each section can be set separately, which means the sharing portion that the DSO needs to bear in case of deviation of actual expenditure from forecast cost at different R can be adjusted accordingly.

$$SF = \left(R - R_{reference}\right) \cdot SF_{slope} + SF_{reference}$$

A piecewise linear SF function with 3 sections has been designed. The values that need to be determined in this function are the R where the functions join, the slope of each section and the reference SF. The two joining points which join the three sections of linear functions can be chosen according to the range of R being defined in the menu of contracts. The slope of each section is set to be increasingly negative when R increases.

Only one reference SF at a specific R need to be set. The SF at the joining point at the section that has been defined is set to be the reference value of the other section.

$$SF2_{reference} = \left(R_{joining-point} - R1_{reference}\right) \cdot SF1_{slope} + SF1_{reference}$$

By doing the same calculation to all functions of the other sections, the whole piecewise linear function can be obtained. Figure 3 shows an example of the SF function produced by using a piecewise linear function.

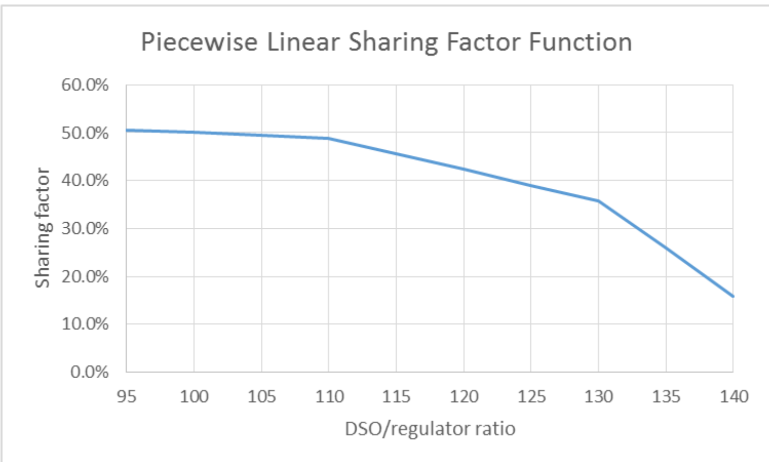

Figure 3 Piecewise linear SF function

Quadratic Function

The SF is computed with quadratic function of R, where R represents the DSO/regulator ratio.

$$SF = \sigma_1 R^2 + \sigma_2 R + \sigma_3$$

As SF changes with R with increasingly negative slope, term "σ_1" needs to be a negative number so that graph of SF will be concave down. The desired shape of graph and rate of change of slope can be produced by adjusting the values of "σ_1". The closer is the value of "σ_1" to zero, the smaller the rate of change of the downward slope.

Consider the fact that negative quadratic function will always have a peak, there is a point R before which the incentive will increase with increasing R and this is in contrast with the desired SF. As SF function only need to have downward slope, the useful range of this function is the part after peaking point. Thus, in this case, the R with lowest value being considered in the menu of contracts is set to be the point which produce the peak in the function. Point R where the function reaches its peak can be calculated by formula

$$R = \frac{-\sigma_2}{2\sigma_1}$$

Hence, term "σ_2" in the quadratic function can be computed by the formula below, with R equal to the lowest DSO/regulator ratio, so that only the adequate range is being considered.

$$\sigma_2 = -2\sigma_1 \cdot R$$

The term "σ_3" can be computed by taking in the desired values of SF at a reference point R, using the equation below.

$$\sigma_3 = SF_{reference} - \sigma_1 {R_{reference}}^2 - \sigma_2 R_{reference}$$

An example of sharing factor with quadratic function is shown in Figure 4.

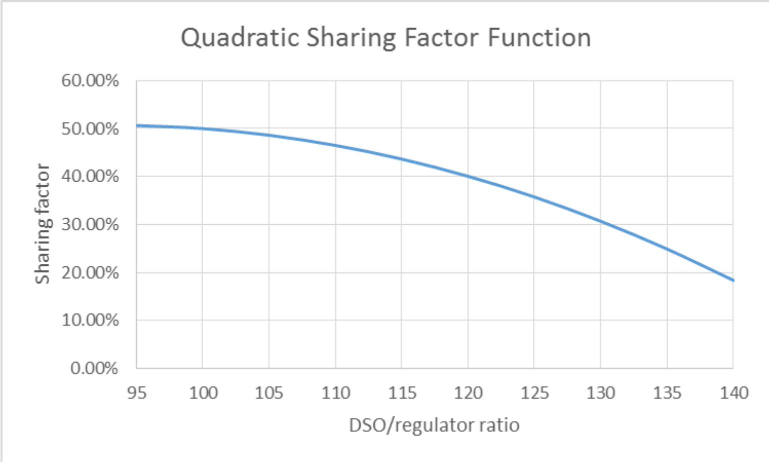

Figure 4 Quadratic SF function

<u>Cubic Function</u>

The SF is computed with cubic function of R, where R represents the DSO/regulator ratio.

$$SF = \sigma_1 R^3 + \sigma_2 R^2 + \sigma_3 R + \sigma_4$$

The desired shape of SF function and degree of the rate of change of slope can be modified by adjusting the values of "σ_1", "σ_2" and "σ_3". However, for the sake of simplicity, only the terms "σ_1" and "σ_3" will be discussed while term "σ_2" is kept as zero.

To produce SF function with downward ending when R increases, the term "σ_1" needs to be smaller than zero. The smaller the magnitude of "σ_1", the smaller the rate of change of in gradient in the downward slope.

The term "σ_3" needs to be negative also. The modification of the shape of graph at smaller range of R can be done by adjusting the value of "σ_3". A less negative "σ_3" produces flatter curve at lower R while a more negative "σ_3" produces sharper slope at the lower R. At larger R, the impact of the change in "σ_1" is higher because "σ_1" is the coefficient of R^3, compare to the impact by changing "σ_3", which is the coefficient of R. In comparison to "σ_1", the tuning of "σ_3" changes the graph more at lower range of R while the tuning of "σ_1" changes the graph more at higher range of R.

The last term, "σ_4" is a constant and it can be computed by using reference SF and R with the equation below.

$$\sigma_4 = SF_{reference} - \sigma_1 R_{reference}{}^3 - \sigma_2 R_{reference}{}^2 - \sigma_3 R_{reference}$$

The combine tuning of "σ_1" and "σ_3" can produce a graph with the desired change in slope. Thus, it is more flexible to obtain the desired shape of the graph by using cubic function compared to quadratic function. Figure 5 shows the graph of SF using cubic function.

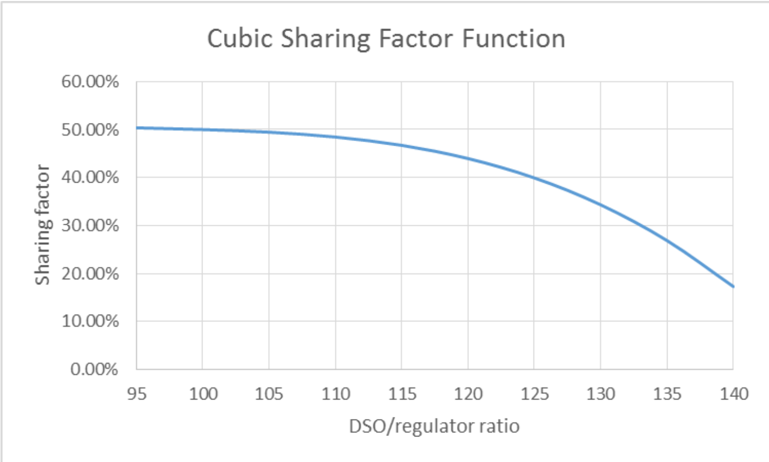

Figure 5 Cubic SF function

4.2.2 Concave Up Sharing Factor Function

<u>Piecewise Linear Function</u>

The SF is calculated by using piecewise linear function with decreasing downward slope when R increases. The procedure, calculations and equations needed to obtain a piecewise linear concave up SF function is the same as that in obtaining a piecewise linear concave down SF function, except the slopes of different sections need to be set at decreasing magnitude. Figure 6 shows the graph of SF using piecewise linear function.

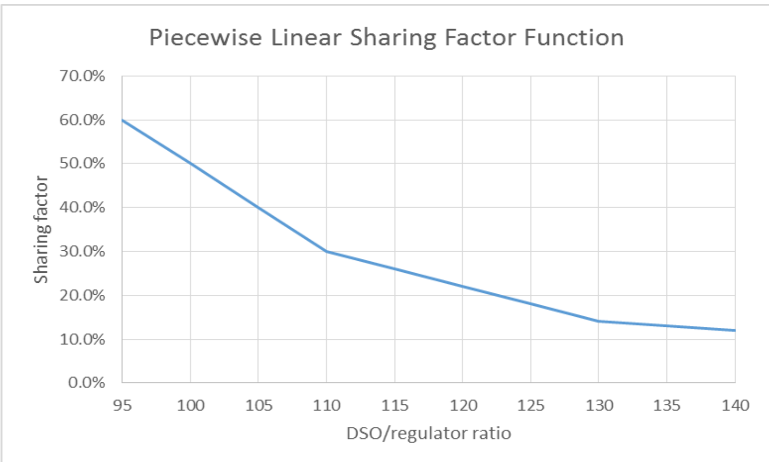

Figure 6 Piecewise linear SF function

Quadratic Function

There are two differences in the calculation of quadratic function's parameters to obtain a concave up SF and a concave down SF.

$$SF = \sigma_1 R^2 + \sigma_2 R + \sigma_3$$

Firstly, in a concave up SF, the SF changes with R with decreasing negative slope, term "σ_1" needs to be a positive number so that graph of SF will be concave up. By adjusting the values of "σ_1", the desired shape of graph and rate of change of slope can be produced. The smaller the value of "σ_1", the smaller the rate of change of the downward slope, the flatter the function will be.

Secondly, the bottom of the positive quadratic function need to be define so that only the decreasing part of the function is being considered in the SF function. Hence, the highest DSO/regulation ratio is taken as the point where the quadratic function reaches its bottom. Point R where the function reaches its bottom can be calculated by formula

$$R = \frac{-\sigma_2}{2\sigma_1}$$

By rearranging the equation, "σ_2" can be obtained by setting R to the highest DSO/regulator ratio.

$$\sigma_2 = -2\sigma_1 \cdot R$$

Likewise, term "σ_3" can be computed by taking in the desired values of SF at a reference point R, using the equation below.

$$\sigma_3 = SF_{reference} - \sigma_1 {R_{reference}}^2 - \sigma_2 R_{reference}$$

An example of sharing factor graph with quadratic function is shown in Figure 7.

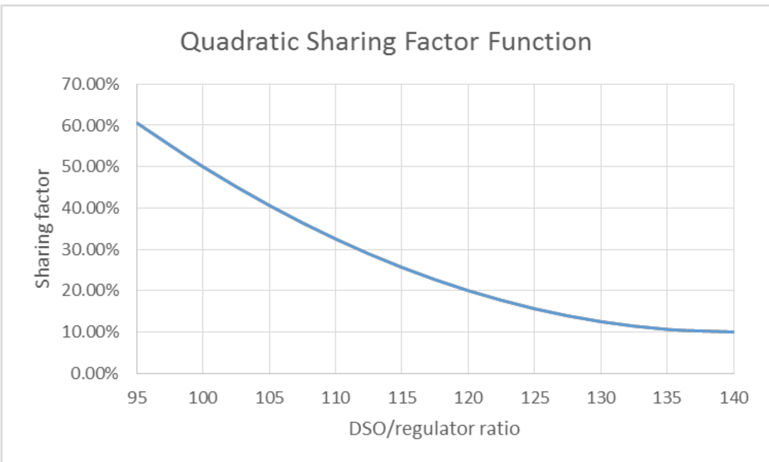

Figure 7 Quadratic SF function

4.2.3 Linear Upward and Downward Asymmetry Sharing Factor Function

An asymmetry SF function rewards outperformance and penalizes underperformance at different rate. If a SF function is used for outperformance and another SF function is used for underperformance, there will be two SF functions used within the same column. As a consequence, it is possible to have rewards within the same row computed by two different SF functions, which will create discontinuity and will not ensure incentive compatibility. Table 2 shows an example when rewards are computed by two different SF functions, where the grey cells represent cases when actual expenditure higher than allowed revenue while the green cells represent cases when actual expenditure lower than allowed revenue.

Ratio DSO/Regulator	**95**	**100**	**105**	**110**	**115**	**120**	**125**	**130**	**135**	**140**
Allowed revenues	98	100	102	104	106	108	110	112	114	116
105										

Table 2 Example showing situation when rewards are computed by using two SF functions

Thus, asymmetry SF functions which change linearly with the difference between actual expenditure and allowed revenue have been designed. With this design, only one SF function is used in the whole menu of contracts. Therefore, continuity of reward function in a row and incentive-compatibility can be ensured. A linear SF function is used as the basic in designing the asymmetry SF function, thus the reference SF decreases linearly with DSO/regulator ratio. The asymmetry SF functions vary around the reference SF, either increases or decreases with the actual expenditure. These two types of asymmetry SF functions are discussed here.

<u>Linear Upward Asymmetry Function</u>

Upward asymmetry means that under the same DSO/regulator ratio, the SF increases with the actual expenditure. The first step is to compute a linear SF function which will acts as reference SF for the asymmetry.

$$SF_1 = (R - R_{reference}) \cdot SF_{slope} + SF_{reference}$$

Then, the SF for each DSO/regulator ratio is further elaborated so that it varies with actual expenditure. This is done by adding a term to the first SF function and the new sharing factor function is shown in the equation below. A new parameter "rate of change (ROC)" is used to indicate how the SF changes in relation to the actual expenditure.

$$SF = SF_1 + (E - AR) \cdot \mathrm{ROC}$$

Where

E = actual expenditure

ROC= constant rate of change of SF with actual expenditure in relation to difference between the actual expenditure and allowed revenue

With this function, the SF calculated in the first step is used as a reference when actual expenditure equals to ex-ante allowed revenue. Since this SF function is a function of both DSO/regulator ratio and actual expenditure, the sharing factor in each cell of the menu of contracts is different.

To get a linear upward asymmetry SF function, ROC is defined as a positive constant and thus the SF increases linearly with actual expenditure. This implies, the higher the amount of overspend (cost saving), the higher (lower) the sharing factor is. The magnitude of ROC defines how sensitive the change of SF is to the actual expenditure. A higher ROC magnitude will result in faster SF changes with actual expenditure.

SF is a linear function of E and AR is a linear function of E also. Based on the reward function, reward will be a quadratic function of E. With positive ROC, reward is a quadratic function with negative "a" and with a peak.

$$Reward = (AR - E) \cdot SF + AI$$
$$Reward = aE^2 + bE + c$$

At constant DSO/regulator ratio, reward should decrease with actual expenditure. The peak of the quadratic reward function should be set so that reward function will only go in the correct direction. Since the quadratic reward function is formed by having SF function with positive ROC across actual expenditure, ROC should be set to a limit.

$$\begin{aligned}
Reward &= (AR - E) \cdot SF + AI \\
&= -ROC \cdot E^2 \\
&\quad + \big(AR \cdot ROC - SF_{reference} - R \cdot SF_{slope} + R_{reference} \cdot SF_{slope} + AR \\
&\quad \cdot ROC\big) \cdot E + AR \cdot SF_{reference} + AR \cdot R \cdot SF_{slope} - AR \cdot R_{reference} \cdot SF_{slope} \\
&\quad - AR^2 \cdot ROC + AI
\end{aligned}$$

By expanding the reward function, coefficient "a", "b" and "c" of the quadratic function are obtained. Since reward always decrease with actual expenditure, the peak of reward should be at least at the lowest actual expenditure being considered in the menu of contracts. Point E where the function reaches its peak can be calculated by equation

$$E = \frac{-b}{2a}$$

After substituting "a", "b" and E into the equation above and rearranging the equation, the limit of ROC is obtained.

$$ROC = \frac{SF_{reference} + R \cdot SF_{slope} - R_{reference} \cdot SF_{slope}}{2 \cdot (AR - E_{lowest})}$$

The value of ROC which is obtained by substituting the minimum actual expenditure will be the highest limit of ROC. Any positive values below this limit can be used to adjust the sensitivity of changes in SF. Figure 8 shows how a linear upward asymmetry SF function changes with actual expenditure.

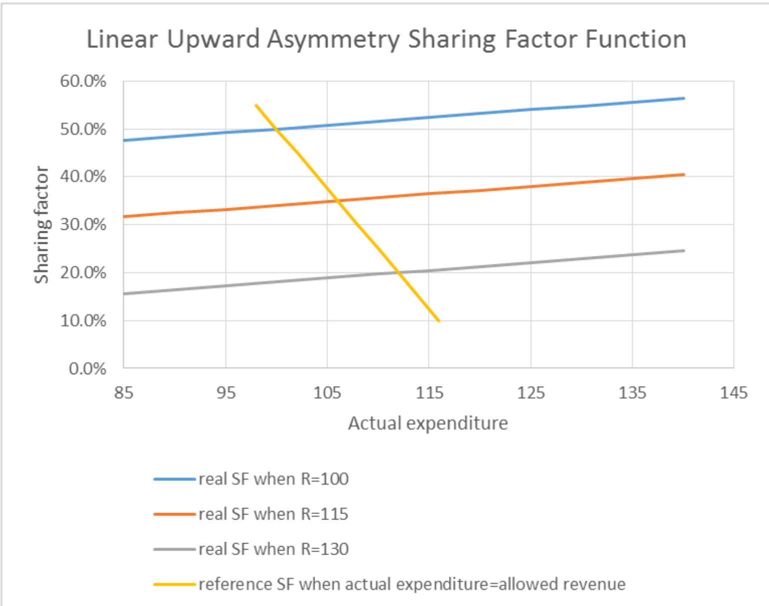

Figure 8 Linear upward asymmetry SF function

Linear Downward Asymmetry Function

Downward asymmetry means that under the same DSO/regulator ratio, the sharing factor decreases with the actual expenditure. In this SF function, the ROC is defined as a negative constant. This makes the sharing factor to decrease linearly as actual expenditure gets larger. This implies that the higher the amount of overspend (cost saving), the lower (higher) the SF will be. The magnitude of ROC will determine how sensitive is the changes of SF to actual expenditure. A more negative ROC will result in faster SF decrement with actual expenditure.

With negative value of ROC, the reward becomes a quadratic function with positive "a" and with a bottom. Since reward decreases with actual expenditure under constant DSO/regulator ratio, the bottom of reward function should be defined at most at the point where actual expenditure is the largest.

$$ROC = \frac{SF_{reference} + R \cdot SF_{slope} - R_{reference} \cdot SF_{slope}}{2 \cdot (AR - E_{highest})}$$

The limit of ROC can be obtained by substituting the maximum actual expenditure into the equation. Any negative values between this limit and zero are within the feasible range of ROC. Figure 9 shows how a linear downward asymmetry SF function changes with actual expenditure.

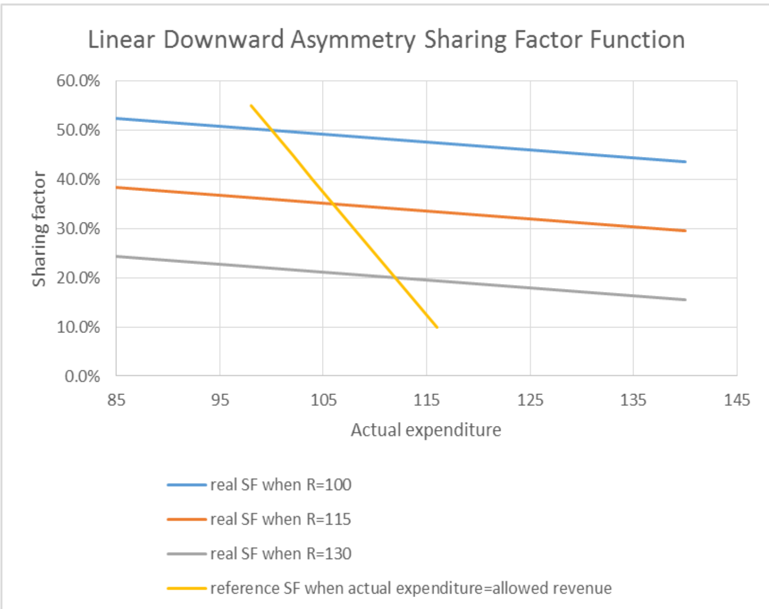

Figure 9 Linear downward asymmetry SF function

4.3 Additional Income

The next step is to calculate the additional income as a function of DSO/regulator ratio. Additional income is the extra payment to the firms in order to make sure that the menu is incentive-compatible. The functional forms for additional income that had been used in (Cossent & Gómez, 2013) and (Oxera, 2007) are quadratic function of DSO/regulator ratio, both correspond to linear function SF. An additional income function need to be derived specifically for each SF functions. There are four functional forms which are used for SF functions, they are piecewise linear function (concave down and concave up), quadratic function (concave down and concave up), cubic function (concave down) and linear asymmetry function. The derivation of the additional income functions for each SF functional forms will be presented in this section.

4.3.1 Piecewise Linear Sharing Factor Function

The calculation of additional income for the piecewise linear function is again consist of three parts, one for each section of the SF. The same method to calculate additional income for linear SF as derived by (Cossent & Gómez, 2013) has been used for each section. The equations used are shown as below.

$$AI = \gamma + \alpha \cdot R + \beta \cdot R^2$$
$$\alpha = SF_{reference} \cdot (w-1) + SF_{slope} \cdot [R_{reference} \cdot (1-w) - 100w]$$
$$\beta = SF_{slope} \cdot (w - 0.5)$$
$$\gamma = AI_{reference} - \alpha \cdot R_{reference} - \beta \cdot {R_{reference}}^2$$

In this case, the reference additional income only need to be set for one section. The joining points are defined to be the reference R and the reference additional income at these points are calculated from the section which the references have been set.

$$\gamma_2 = \gamma_1 + \alpha_1 \cdot R_{joining-point} + \beta_1 \cdot {R_{joining-point}}^2$$

4.3.2 Quadratic Sharing Factor Function

Additional income with cubic function of R is used together with a quadratic SF function. Reward is calculated by substituting the known functions of allowed expenditure and SF into the reward function:

$$Reward = (AR - E) \cdot SF + AI$$
$$AR = w \cdot 100 + (1 - w) \cdot R$$
$$SF = \sigma_1 R^2 + \sigma_2 R + \sigma_3$$
$$AI = \alpha_1 R^3 + \alpha_2 R^2 + \alpha_3 R + \alpha_4$$

$$\begin{aligned} Reward &= (AR - E) \cdot SF + AI \\ &= (\sigma_1 - w\sigma_1 + \alpha_1)R^3 + (100w\sigma_1 + \sigma_2 - w\sigma_2 - E\sigma_1 + \alpha_2)R^2 \\ &\qquad + (100w\sigma_2 + \sigma_3 - w\sigma_3 - E\sigma_2 + \alpha_3)R + 100w\sigma_3 + \alpha_4 - E\sigma_3 \end{aligned}$$

The reward received by firm is maximum when the first derivative of reward function with respect to R is equal to zero and this should happen whenever the actual expenditure is equal to R (Cossent & Gómez, 2013). The calculation of additional income function is included in Appendix C.

The calculation shows that the coefficient of the additional income can be computed by

$$\alpha_1 = \frac{3w\sigma_1 - \sigma_1}{3}$$
$$\alpha_2 = \frac{2w\sigma_2 - \sigma_2 - 200w\sigma_1}{2}$$
$$\alpha_3 = w\sigma_3 - 100w\sigma_2 - \sigma_1$$

α_4 will not affect the incentive compatibility of the menu of contracts and hence, the regulator is free to determine α_4 by taking into account the overall profitability of the menu matrix desired. By equating the equation of additional income to the reference value of additional income when R equals to certain value, α_4 can be determined.

$$\alpha_4 = AI_{reference} - \alpha_1 {R_{reference}}^3 - \alpha_2 {R_{reference}}^2 - \alpha_3 R_{reference}$$

4.3.3 Cubic Sharing Factor Function

Additional income with quadratic function of R is used together with a cubic SF function. Reward is calculated by substituting the known functions of allowed expenditure and sharing factor into the reward function:

$$Reward = (AR - E) \cdot SF + AI$$
$$AR = w \cdot 100 + (1 - w) \cdot R$$
$$SF = \sigma_1 R^3 + \sigma_2 R^2 + \sigma_3 R + \sigma_4$$
$$AI = \alpha_1 R^4 + \alpha_2 R^3 + \alpha_3 R^2 + \alpha_4 R + \alpha_5$$

$$\begin{aligned} Reward &= (AR - E) \cdot SF + AI \\ &= (\sigma_1 - w\sigma_1 + \alpha_1)R^4 + (100w\sigma_1 + \sigma_2 - w\sigma_2 - E\sigma_1 + \alpha_2)R^3 \\ &\quad + (100w\sigma_2 + \sigma_3 - w\sigma_3 - E\sigma_2 + \alpha_3)R^2 \\ &\quad + (100w\sigma_3 + \sigma_4 - w\sigma_4 - E\sigma_3 + \alpha_4)R + 100w\sigma_4 - E\sigma_4 + \alpha_5 \end{aligned}$$

The reward received by firm is maximum when the first derivative of reward function with respect to R is equal to zero and this should happen whenever the actual expenditure is equal to R (Cossent & Gómez, 2013). The calculation of this additional income function is included in Appendix D.

The calculation shows that the coefficient of the additional income can be computed by

$$\alpha_1 = \frac{4w\sigma_1 - \sigma_1}{4}$$
$$\alpha_2 = \frac{3w\sigma_2 - 300w\sigma_1 - \sigma_2}{3}$$
$$\alpha_3 = \frac{2w\sigma_3 - 200w\sigma_2 - \sigma_3}{2}$$
$$\alpha_4 = w\sigma_4 - 100w\sigma_3 - \sigma_4$$

α_5 will not affect the incentive compatibility of the menu matrix and hence, the regulator is free to determine α_5 by taking into account the overall profitability of the menu matrix desired. By equating the equation of additional income to the reference value of additional income when R equals to certain value, α_5 can be determined.

$$\alpha_5 = AI_{reference} - \alpha_1 R_{reference}{}^4 - \alpha_2 R_{reference}{}^3 - \alpha_3 R_{reference}{}^2 - \alpha_4 R_{reference}$$

4.3.4 Linear Asymmetry Sharing Factor Function

Additional income with quadratic function of R is used together with the linear asymmetry SF function. Reward is calculated by substituting the known functions of allowed expenditure and sharing factor into the reward function:

$$Reward = (AR - E) \cdot SF + AI$$
$$AR = w \cdot 100 + (1 - w) \cdot R$$
$$SF = \left(R - R_{reference}\right) \cdot SF_{slope} + SF_{reference} + (E - AR) \cdot ROC$$
$$AI = \alpha_1 \cdot R^2 + \alpha_2 \cdot R + \alpha_3$$

The reward received by firm is maximum when the first derivative of reward function with respect to R is equal to zero and this should happen whenever the actual expenditure is equal to R (Cossent & Gómez, 2013). The calculation of this additional income function is included in the Appendix E.

The calculation shows that the coefficient of the additional income can be computed by

$$\alpha_1 = \frac{SF_{slope} \cdot (2w - 1) + 2 \cdot ROC \cdot w(w - 1)}{2}$$
$$\alpha_2 = SF_{slope}\left(R_{reference} - 100w - R_{reference} \cdot w\right) + 200 \cdot ROC \cdot w(1 - w) + SF_{reference}(w - 1)$$

α_3 will not affect the incentive compatibility of the menu matrix and hence, the regulator is free to determine α_3 by taking into account the overall profitability of the menu matrix desired. By equating the equation of additional income to the reference value of additional income when R equals to certain value, α_3 can be determined.

$$\alpha_3 = AI_{reference} - \alpha_1 R_{reference}{}^2 - \alpha_2 R_{reference}$$

4.4 Summary

Four functions are used to derive SF and by understanding the significances of parameters in these functions, the shape of SF function can be adjusted to the desired one. Table 3 summarizes the allowed revenue function, four SF functions, the significances of their parameters and the corresponding additional income functions to construct a menu of contracts. The details used to construct menu of contracts with the four SF functional forms are included in Appendix F, G, H and I.

	Piecewise Linear	Quadratic	Cubic	Linear Asymmetry
Allowed revenue function	$w \bullet 100+(1-w) \bullet R$			
Parameters that need to be defined and their significances	- w = weightage given to the cost estimated by regulator - R = DSO forecast cost/regulator's benchmark			
Sharing factor function	Three linear sections of $(R-R_{ref}) \bullet SF_{slope} + SF_{ref}$	$\sigma_1 R^2 + \sigma_2 R + \sigma_3$	$\sigma_1 R^3+\sigma_2 R^2+\sigma_3 R+\sigma_4$	$(R-R_{ref}) \bullet SF_{slope} + SF_{ref} + (E-AR) \bullet ROC$
Parameters that need to be defined and their significances	- SF_{slope} = a negative constant which define the slope of SF across R - SF_{ref} and R_{ref} are set according to the desired reference values	- σ_1: Negative "σ_1" produces a concave down SF function while positive "σ_1" produces a concave up SF function. The larger the magnitude of "σ_1", the higher the rate of change of the slope. - $\sigma_2 = -2a \bullet R$ - σ_3: "σ_3" is calculated by equating SF and R to the desired reference values.	- σ_1: Negative "σ_1" produces a concave down SF function. The larger the magnitude of "σ_1", the higher the rate of change of the slope. The tuning of "σ_1" changes the graph more at higher range of R. - σ_2: set to zero for simplicity - σ_3: "σ_3" is a negative constant. The smaller the "σ_3", the higher the rate of change of the slope. The tuning of "σ_3" changes the graph more at lower range of R. - "σ_4" is calculated by equating SF and R to the desired reference values.	- E = actual expenditure - SF_{slope} = a negative constant which define the slope of the SF across DSO/regulator ratio. - ROC is the constant rate of change of SF across actual expenditure in relation to difference between the actual expenditure and allowed revenue. - Negative "ROC" produces SF which decreases with actual expenditure while positive "ROC" produces SF which increases with actual expenditure. - SF_{ref} and R_{ref} are set according to the desired reference values.
Additional income function	$\gamma+\alpha R+\beta R^2$	$\alpha_1 R^3+\alpha_2 R^2+\alpha_3 R+\alpha_4$	$\alpha_1 R^4+\alpha_2 R^3+\alpha_3 R^2+\alpha_4 R+\alpha_5$	$\alpha_1 R^2+\alpha_2 R+\alpha_3$
Parameters that need to be defined and their equations	- $\alpha=SF_{ref} \bullet (w-1) +SF_{slope} \bullet [R_{ref} \bullet (1-w)-100w]$ - $\beta=SF_{slope} \bullet (w-0.5)$ - $\gamma=AI_{ref}-\alpha R_{ref}-\beta R_{ref}^2$	- $\alpha_1=(3w\sigma_1-\sigma_1)/3$ - $\alpha_2=(2w\sigma_2-\sigma_2-200w\sigma_1)/2$ - $\alpha_3=w\sigma_3-100w\sigma_2-\sigma_1$ - $\alpha_4=AI_{ref}-\alpha_1 R^3-\alpha_2 R^2-\alpha_3 R$	- $\alpha_1=(4w\sigma_1-\sigma_1)/4$ - $\alpha_2=(3w\sigma_2-300w\sigma_1-\sigma_2)/3$ - $\alpha_3=(2w\sigma_3-200w\sigma_2-\sigma_3)/2$ - $\alpha_4=w\sigma_4-100w\sigma_3-\sigma_4$ - $\alpha_5=AI_{ref}-\alpha_1 R^4-\alpha_2 R^3-\alpha_3 R^2-\alpha_4 R$	- $\alpha_1=(SF_{slope} \bullet (2w-1)+2 \bullet ROC \bullet w(w-1))/2$ - $\alpha_2=SF_{slope}\ (R_{ref}-100w- R_{ref} \bullet w)+200 \bullet ROC \bullet w(1-w)+SF_{ref}\ (w-1)$ - $\alpha_3=AI_{ref} - \alpha_1 R_{ref}^2 - \alpha_2 R_{ref}$

Table 3 Summary of parameters used in menu of contracts

Chapter 5 Quantifying the Impact of PV Adoption on Distribution Network Costs

This chapter provides the input data that has been used to generate the reference networks and the result obtained at each step. First of all, image processing is run with the specifications of input parameters which can represent the characteristics of the network, including the actual street map, estimated number of residents per buildings, probability of resident and commercial, power factors and load density. This step is done in order to identify the total number of low voltage and medium voltage electricity consumers, their GPS coordinates and the power needed, which are then being applied to the greenfield model. The input data for these parameters are shown in Table 4.

	Rural	Urban
Estimated number of residents per buildings	3	20
Commercial power factor	0.98	0.98
Residential power factor	0.95	0.95
Probability of having commercial customers	0.01	0.05
Probability of having residential customers	100	100
Power probability of commercial customers (kW)	100, 50% 200, 50%	100, 50% 200, 50%
Power probability of residential customers (kW)	3.45, 33% 4.6, 33% 6.9, 24% 9.2, 10%	3.45, 33% 4.6, 33% 6.9, 24% 9.2, 10%

Table 4 Input data for image processing

The total number of low voltage and medium voltage electricity consumers, the GPS coordinates and the power needed that have been obtained from image processing are used in the greenfield model to generate a network which is optimally adapted to demand. The results obtained from greenfield model for both rural and urban area are shown in Table 5.

	Rural	Urban
Population	23867	117211
LV supply points	7646	6003
MV supply points	0	6
Contracted power (MW)	123.35	614.15
Peak demand (MW)	49.74	246.07
Yearly energy consumed (MWh)	152503.64	754454.18
Length of LV line (km)	121.09	115.80
Length of MV line (km)	42.10	60.41
Length of HV line (km)	4.24	13.72

Table 5 Results obtained from greenfield model

Brownfield model is used to generate the new distribution network to obtain the estimated investment cost for the diverse set of potential scenarios in the future. Nine scenarios representing possible levels of PV penetration, which are from 10% to 90% of the total population have been modelled for each area. The percentage of PV penetration is definedas:

$$PV\ penetration\ (\%) = \frac{number\ of\ PV\ installed}{number\ of\ consumers} \cdot 100$$

During the network expansion, the PV panels are located randomly in the existing load point of the distribution areas and the output of each PV panels are set to between 2 to 7 kW. Two snapshots are considered in all scenarios, which are during peak generation and peakdemand periods. The necessary reinforcements that are needed to support the networks duringthese snapshots are computed. Peak generation and peak demand periods for low voltage and medium voltage consumers have been identified as between hour 12 to 14 and hour 20 to 22 respectively from the hourly standard load profiles of Spain in 2016 (Red Eléctrica de España, 2017). The simultaneity factors during peak demand period for low voltage and medium voltage consumers are set to 0.4 and 0.8 respectively. The ratios of peak generation's simultaneity factor to peak demand's simultaneity factor are determined as the ratioofpower used during peak generation to that during peak demand. With the power used during both period obtained from the standard load profile, the simultaneity factor during peak generation can be calculated. Table 6 shows the simultaneity factor that have been used in brownfield model.

	LV	MV
Peak demand	0.4	0.8
Peak generation	0.27	1.25

Table 6 Simultaneity factors used during snapshots

Table 7 and Table 8 show the generation from PV panels during peak demand and peak generation at different level of PV penetration.

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%
Peak demand period	2148	4296.8	6456.4	8632.8	10786.8	12947	15102.8	17218.8	19330.6
Peak generation period	8592	17187.2	25825.6	34531.2	43147.2	51788	60411.2	68875.2	77322.4

Table 7 The PV generations different periods of the day in rural

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%
Peak demand period	10560	21111.6	31586	42103.2	52657.8	63260	73847.2	84418.2	95006.4
Peak generation period	42240	84446.4	126344	168412.8	210631.2	253040	295388.8	337672.8	380025.6

Table 8 The PV generations different periods of the day in urban

The graphs in Figure 10 and Figure 11**Error! Reference source not found.** show the demand and the amount of electricity generated by PV at different levels of penetration during peak demand and peak generation period in rural area. During peak demand period, electricity demand is still higher than that generated by PV panels even under the scenari o of 90% PV penetration. While during peak generation period, the PV generation is able to exceed the demand when the penetration level is higher than 40%.

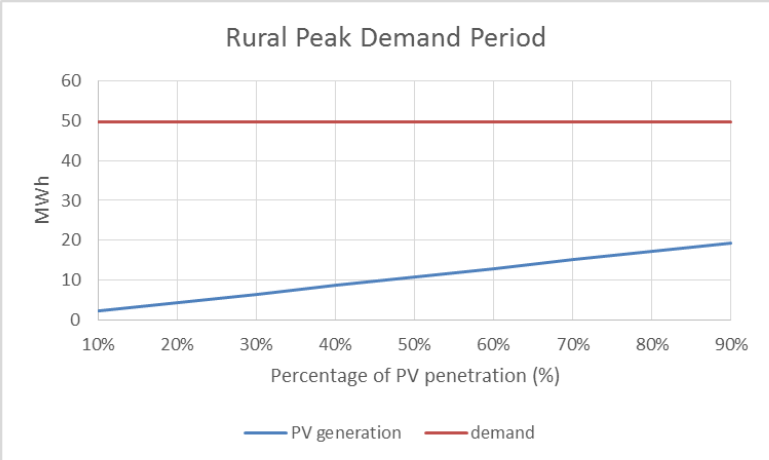

Figure 10 Peak demand period in rural area

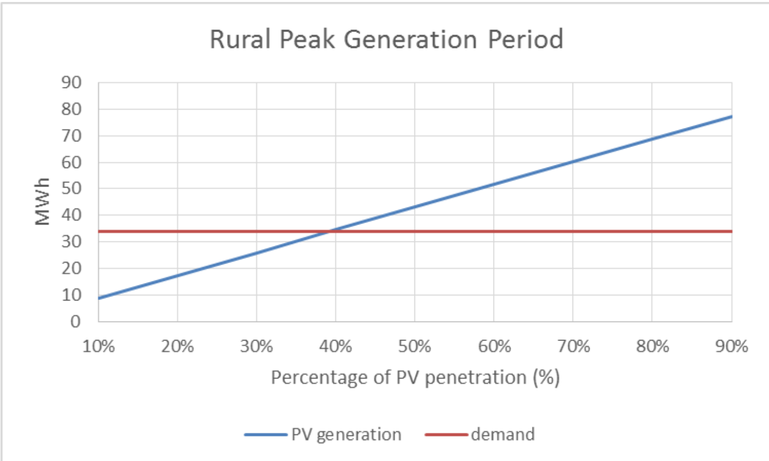

Figure 11 Peak generation period in rural area

The graphs in Figure 12 and Figure 13 show the demand and the amount of electricity generated by PV at different levels of penetration during peak demand and peak generation period in urban area. As in the case of rural area also, electricity demand in urban area is higher than that generated by PV panels during peak demand period even when the penetration level is 90%. On the other hand, the PV generation is able to exceed the demand when the penetration level is higher than 40% during peak generation period.

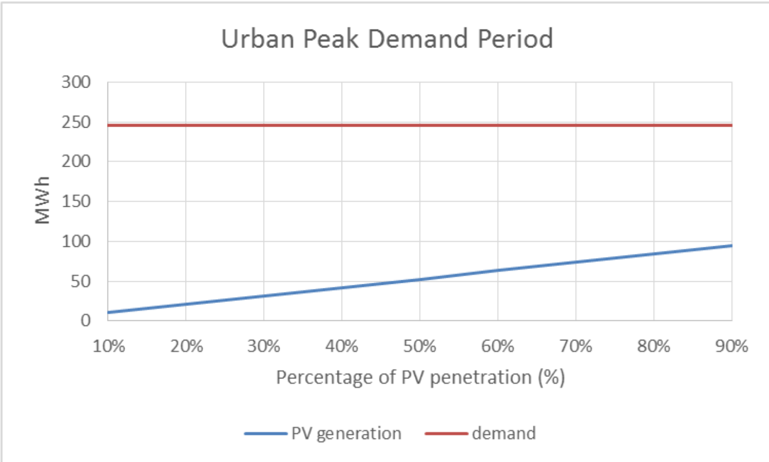

Figure 12 Peak demand period in urban area

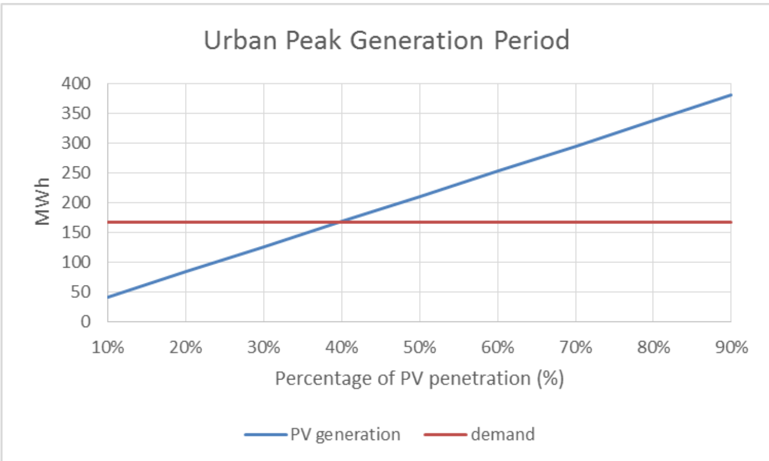

Figure 13 Peak generation period in urban area

The resulted total investment cost in net present value simulated from the brownfield models are shown in the Table 9, Figure 14 and Figure 15 below. As can be seen from the figures, the investment cost increases gradually with the increase in PV panels' installation. The breakdowns of investment cost in rural and urban area are included in Appendix J and K.

	Rural	Urban
10.00%	0	8154
20.00%	0	0
30.00%	7916	0
40.00%	885853	0
50.00%	4563047	48657
60.00%	6595143	182551
70.00%	8338355	636212
80.00%	10883799	1722673
90.00%	13164373	3021498

Table 9 Total investment cost at different levels of PV penetration

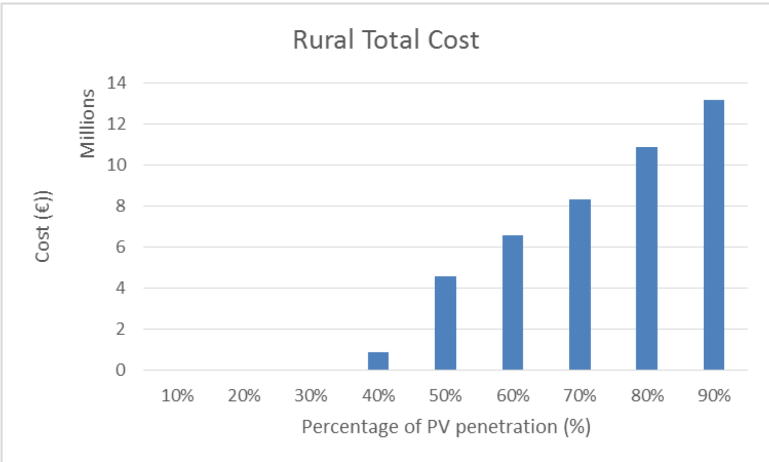

Figure 14 Total investment cost in rural area

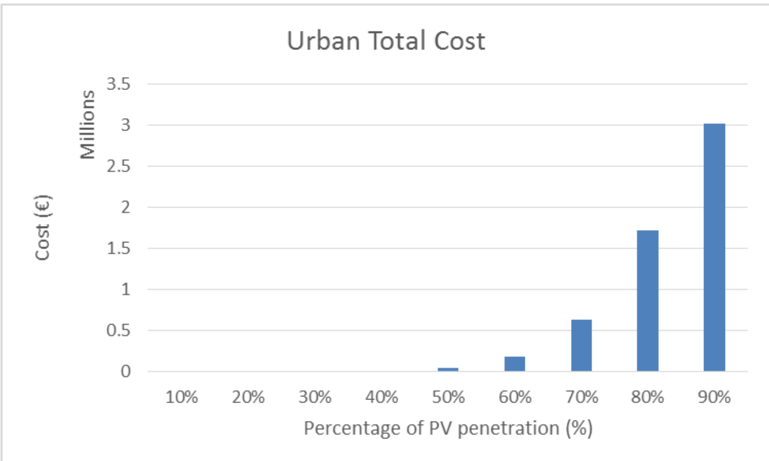

Figure 15 Total investment cost in urban area

Chapter 6 Comparison Menus of Contracts' Properties by Using Different Sharing Factor Functions and RNM's Investment Cost Estimation

There are a few reasons which can cause the differences between the DSO's forecast, regulator's benchmark and the actual expenditure, including DSO inflated forecast, benchmark errors and uncertainties about the future PV penetration. Thus, it will be useful to conduct analyses under situations when DSO inflates the forecast cost, spends lower than the forecast cost and spends more than the forecast cost. In this chapter, the impacts of each design of SF on the outcome will be compared to the outcome which uses a linear SF function under these situations and the result will be analysed in detail. All designs of menus of contracts are made comparable by fixing the following parameters: weightage of regulator's estimate is set to 60%, reference SF and reference AI are set to 50% and 2.5 respectively when DSO/regulator ratio is equal to 100. Since the same weightages of regulator's estimate are used, allowed revenue at the same R are the same in all cases. The estimated cost for different levels of PV penetration that have been obtained from RNM are used in the menus of contracts to assume different realizations for regulator's forecast, DSO's forecast and actual expenditure. There are four sections in this chapter, with the first three sections made up of the comparison between the outcomes of concave down, concave up and linear asymmetry SF functions with the outcome of linear SF function, followed by a section which discussed the characteristics of all SF functions designs and their implications.

6.1 Concave Down vs Linear

The main characteristic of concave down SF is that, SF decreases with DSO/regulator ratio at increasing rate. The larger the ratio, the faster the SF changes. Three functional forms have been used to design SF with concave down shape, which are cubic function, quadratic function and piecewise linear function. Since the outcomes of all the three functional forms have the same characteristics, only the cubic concave down SF function is discussed here.

Figure 16 shows a linear SF and a cubic SF functions being plotted on the same graph. This is one of the examples how a concave down SF function can be drawn in relation to a linear SF function. In this example, whenever the DSO's estimated cost is higher than that of regulator, the SF of the cubic function will be higher than the SF of linear function and vice versa. Efficiency incentive, which is the sharing portion of deviation of actual expenditure from allowed revenue that the DSO need to bear, will always have a higher magnitude in this cubic SF function than in linear SF function in this range. The final reward or penalty depends on additional income for each DSO/regulator ratio as reward or penalty is the addition of additional income and efficiency incentive. With these SF functions, the menus of contracts in Table 10 and Table 11 are obtained.

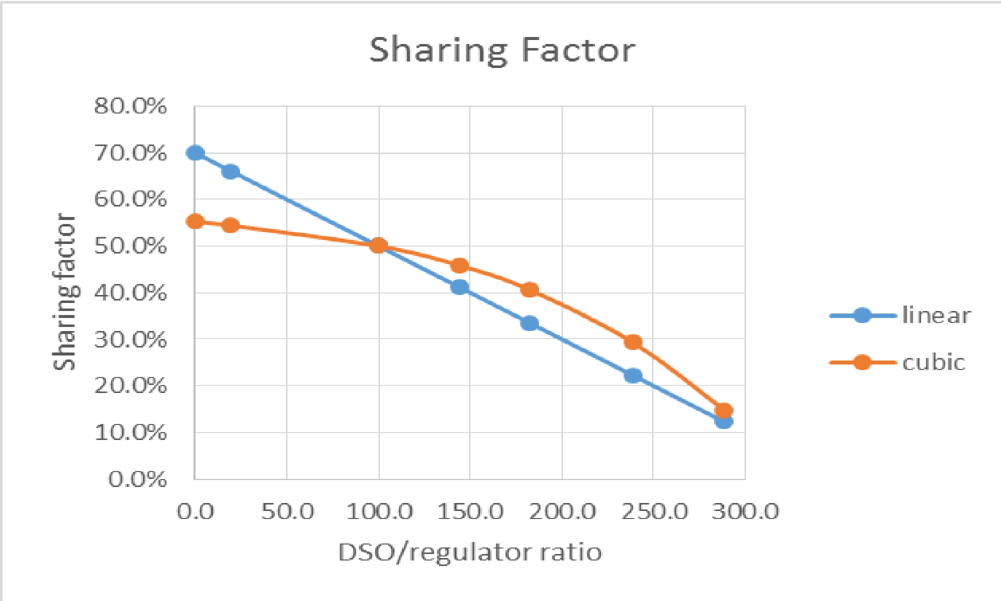

Figure 16 Cubic SF function: a=-1.4e-8, b=0, c=-2.5e-4, $SF_{reference}$=0.5 at R=100; Linear SF function: SF_{slope}=-0.02, $SF_{reference}$=0.5 at R=100

DSO/Regulator ratio	**0.2**	**19.4**	**100.0**	**144.5**	**182.7**	**238.5**	**288.5**
Allowed revenues	60.1	67.8	100.0	117.8	133.1	155.4	175.4
Sharing factor	70.0%	66.1%	50.0%	41.1%	33.5%	22.3%	12.3%
Additional income	20.5	17.3	2.5	-6.8	-15.4	-29.0	-42.3
0.2	62.4	62.0	52.4	41.5	29.0	5.6	-20.8
19.4	48.9	49.3	42.8	33.6	22.6	1.3	-23.1
100.0	-7.5	-4.0	2.5	0.5	-4.3	-16.7	-33.0
144.5	-38.6	-33.4	-19.8	-17.8	-19.2	-26.6	-38.5
182.7	-65.4	-58.7	-38.9	-33.5	-32.0	-35.1	-43.2
238.5	-104.4	-95.6	-66.8	-56.4	-50.7	-47.6	-50.1
288.5	-139.3	-128.6	-91.7	-76.9	-67.4	-58.7	-56.2

Table 10 Menu of contracts using linear SF function

DSO/Regulator ratio	**0.2**	**19.4**	**100.0**	**144.5**	**182.7**	**238.5**	**288.5**
Allowed revenues	60.1	67.8	100.0	117.8	133.1	155.4	175.4
Sharing factor	55.2%	54.4%	50.0%	45.8%	40.6%	29.4%	14.8%
Additional income	22.2	18.4	2.5	-6.7	-15.3	-30.8	-49.6
0.2	55.3	55.2	52.4	47.2	38.6	14.8	-23.6
19.4	44.7	44.8	42.8	38.4	30.8	9.2	-26.5
100.0	0.2	0.9	2.5	1.5	-1.9	-14.5	-38.4
144.5	-24.4	-23.3	-19.8	-18.9	-19.9	-27.6	-45.1
182.7	-45.5	-44.1	-38.9	-36.4	-35.4	-38.8	-50.7
238.5	-76.2	-74.5	-66.8	-61.9	-58.1	-55.2	-59.0
288.5	-103.8	-101.7	-91.7	-84.8	-78.4	-69.9	-66.4

Table 11 Menu of contracts using cubic concave down SF function

Table 12 and Table 13 show the result obtained by the SF functions shown above. The magnitude of reward or penalty given to the DSO in case of cost saving or higher actual expenditure than forecast is higher using cubic SF function compare to that using linear SF function. This is because all the DSO/regulator ratios in the tables are higher than 100, cubic SF are higher than linear SF in all cases, hence the magnitudes of efficiency incentives given to DSO are higher when cubic SF function was used.

Linear SF function	Reference	Inflated DSO estimation	Actual expenditure lower than forecast	Actual expenditure higher than forecast
Regulator's estimate % of penetration	50.00%	50.00%	50.00%	50.00%
DSO's estimate % of penetration	60.00%	70.00%	60.00%	60.00%
Actual % of penetration	60.00%	60.00%	50.00%	70.00%
DSO/Regulator ratio	144.5	182.7	144.5	144.5
Sharing factor (%)	41.1%	33.5%	41.1%	41.1%
Additional income (%)	-6.8	-15.4	-6.8	-6.8
Allowed expenditure	117.8	133.1	117.8	117.8
Actual ratio	144.5	144.5	100.0	182.7
Actual efficiency incentive	-11.0	-3.8	7.3	-26.7
Final remuneration	126.8	125.3	100.5	149.3
Reward/Penalty	**-17.8**	**-19.2**	**0.5**	**-33.5**

Table 12 Table of comparison using linear SF function

Cubic concave down SF function	Reference	Inflated DSO estimation	Actual expenditure lower than forecast	Actual expenditure higher than forecast
Regulator's estimate % of penetration	50.00%	50.00%	50.00%	50.00%
DSO's estimate % of penetration	60.00%	70.00%	60.00%	60.00%
Actual % of penetration	60.00%	60.00%	50.00%	70.00%
DSO/Regulator ratio	144.5	182.7	144.5	144.5
Sharing factor (%)	46.1%	40.8%	46.1%	46.1%
Additional income (%)	-6.7	-15.4	-6.7	-6.7
Allowed expenditure	117.8	133.1	117.8	117.8
Actual ratio	144.5	144.5	100.0	182.7
Actual efficiency incentive	-12.3	-4.7	8.2	-29.9
Final remuneration	125.6	124.5	101.5	146.2
Reward/Penalty	**-19.0**	**-20.0**	**1.5**	**-36.6**

Table 13 Table of comparison using cubic concave down SF function

Inflated DSO's forecast cost

Table 14 and Figure 17 show the outcome when DSO inflates the ex-ante cost estimation at different rate, assuming regulator's estimation and actual cost are 50% and 60% respectively, which makes the actual ratio to be 144.5. The penalty that DSO receives when using menu of contracts with cubic SF function is higher than with linear SF function, which is due to the higher values of cubic SF than linear SF. In addition to that, as the DSO's estimated cost gets higher and the ratio gets larger, the values of the cubic SF decrease at faster rate. With the cubic SF function, DSO is penalized at an increasingly heavy rate compared to that of linear SF function. Hence, DSO is further discouraged from inflating the cost.

DSO's estimate % of penetration	70.00%	80.00%	90.00%
DSO/Regulator ratio	182.7	238.5	288.5
Linear SF function	-19.2	-26.6	-38.5
Cubic SF function	-20.0	-28.1	-47.2

Table 14 Reward/penalty at different inflated forecast

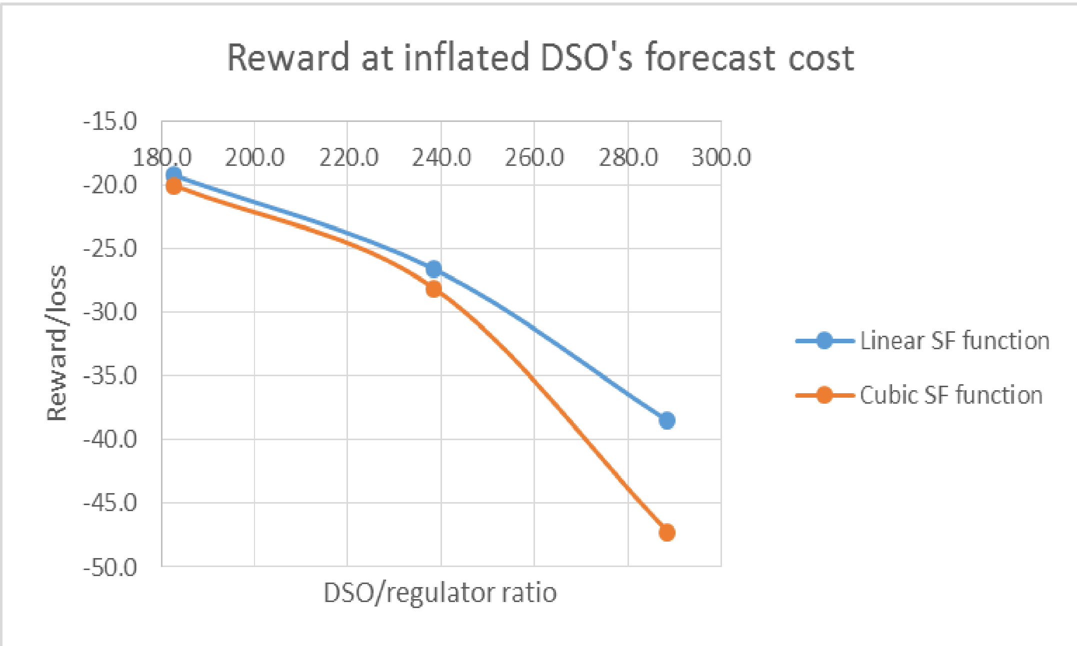

Figure 17 Reward/penalty at different inflated forecast

Actual expenditure lower than forecast

Table 15 and Figure 18 show the outcome when DSO manage to reduce the cost, assuming regulator's and DSO's estimations are 50% and 60% respectively, which makes the DSO/regulator ratio to be 144.5. The more the cost that the DSO manage to reduce, the higher the reward they will earn. In this case, the DSO/regulator ratio is constant and thus the sharing factor is constant as well. Since DSO/regulator ratio is higher than 100, the cubic sharing factor is higher than linear sharing factor, and hence the reward is higher in the menu of contracts with cubic sharing factor.

Actual % of penetration	30.00%	40.00%	50.00%
Actual ratio	0.17	19.4	100
Linear SF function	41.5	33.6	0.5
Cubic SF function	47.5	38.7	1.5

Table 15 Reward/penalty at different level of cost reduction

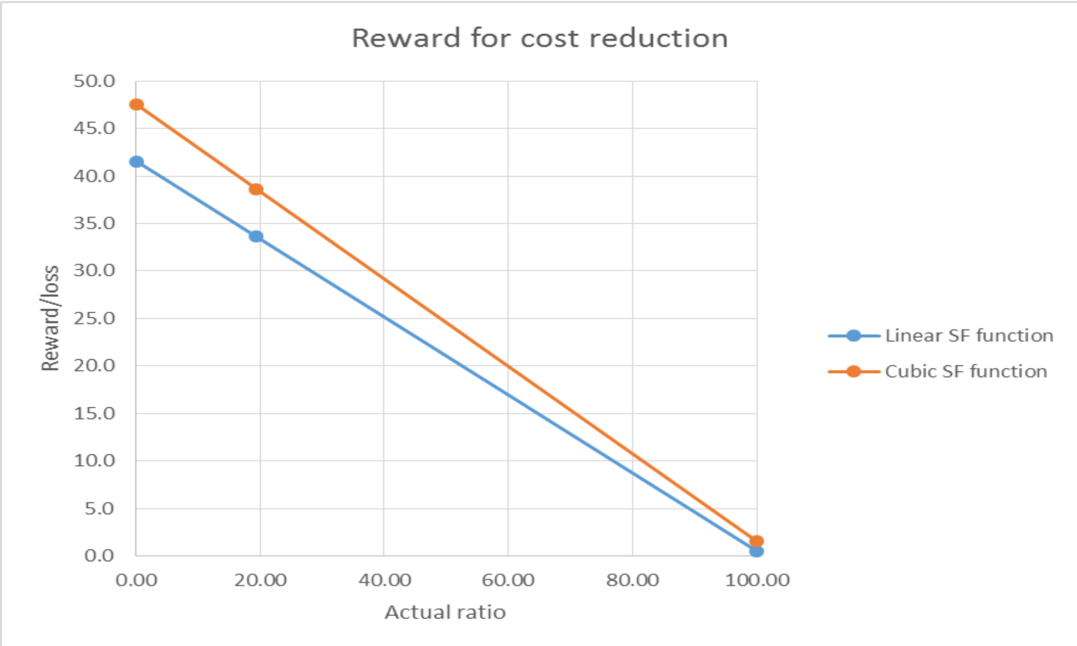

Figure 18 Reward/penalty at different level of cost reduction

Actual expenditure higher than forecast

Table 16 and Figure 19 show the outcome when DSO overrun the cost, assuming regulator's and DSO's estimations are 50% and 60% respectively, which makes the DSO/regulator ratioto be 144.5. This case is the same as in cost reduction. The DSO/regulator ratio is constant and thus the sharing factor also. Since DSO/regulator ratio is higher than 100, the cubic sharing factor is higher than linear sharing factor, and hence the penalty is higher in the menu of contracts with cubic sharing factor.

Actual % of penetration	70.00%	80.00%	90.00%
Actual ratio	182.7	238.5	288.5
Linear SF function	-33.5	-56.4	-76.9
Cubic SF function	-36.6	-62.3	-85.3

Table 16 Reward/penalty at different level of cost overrun

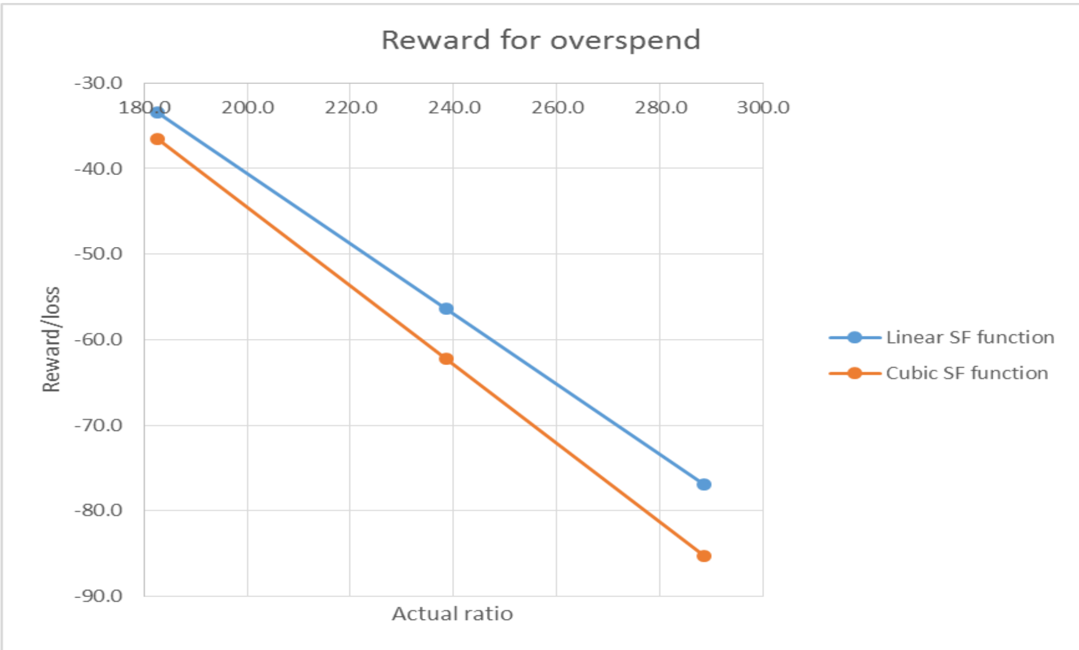

Figure 19 Reward/penalty at different level of cost overrun

6.2 Concave Up vs Linear

The main characteristic of concave up SF functional form is, the SF decreases with R at decreasing rate. The larger the DSO/regulator ratio, the slower the SF changes. A quadratic function and a piecewise linear function had been used to design SF with concave up shape. As the outcomes obtained by using both the functional forms have the same characteristics, only quadratic concave up SF function is discussed.

A linear SF and a quadratic SF are shown in Figure 20. This quadratic function is one of the examples how a concave up SF function can be drawn in relation to a linear SF function, where the SF of quadratic function is lower than that of linear function when DSO/regulator ratio is above 100. Thus, the efficiency incentive will always have a lower magnitude in this quadratic SF function than in linear SF function. However, the final reward or penalty still depends on additional income for each DSO/regulator ratio. The menu of contracts in Table 17 was drawn using this quadratic SF function.

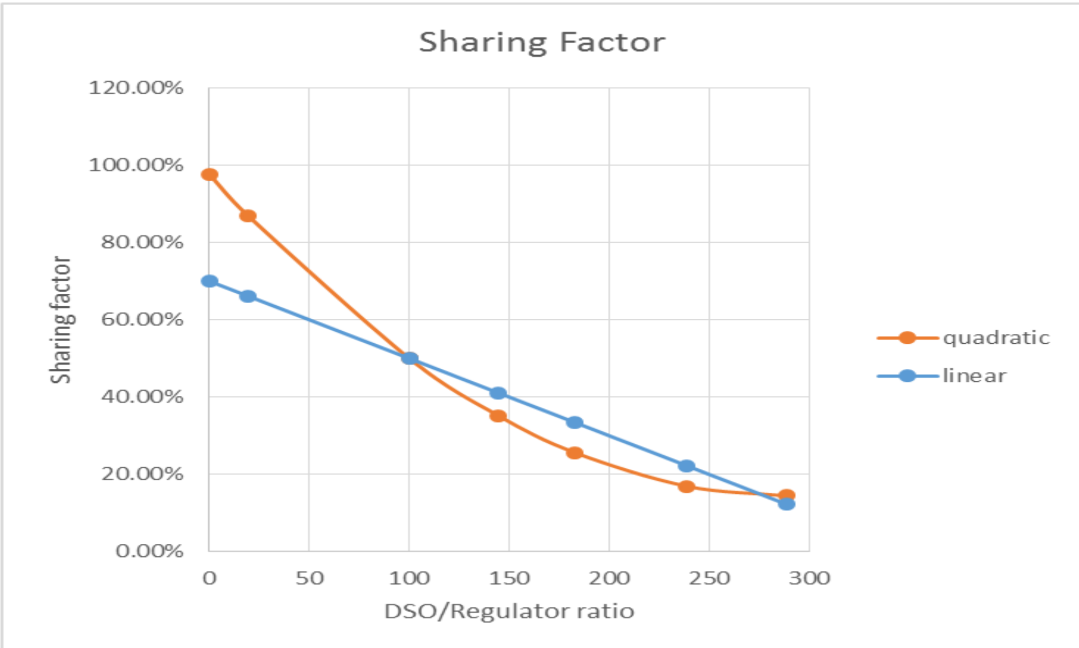

Figure 20 Quadratic SF function: a=1e-5, b=-5.77e-3, $SF_{reference}$=0.5 at R=100; Linear SF function: SF_{slope}=-0.002, $SF_{reference}$=0.5 at R=100

DSO/Regulator ratio	0.2	19.4	100.0	144.5	182.7	238.5	288.5
Allowed revenues	60.1	67.8	100.0	117.8	133.1	155.4	175.4
Sharing factor	97.6%	86.9%	50.0%	35.2%	25.7%	17.0%	14.5%
Additional income	16.1	14.8	2.5	-6.9	-15.1	-25.4	-30.7
0.2	74.5	73.5	52.4	34.5	19.0	1.0	-5.4
19.4	55.7	56.8	42.8	27.7	14.0	-2.3	-8.2
100.0	-22.9	-13.2	2.5	-0.6	-6.6	-15.9	-19.8
144.5	-66.4	-51.9	-19.8	-16.3	-18.1	-23.5	-26.3
182.7	-103.7	-85.1	-38.9	-29.8	-27.9	-30.0	-31.8
238.5	-158.1	-133.6	-66.8	-49.4	-42.2	-39.5	-39.9
288.5	-206.9	-177.0	-91.7	-67.0	-55.0	-47.9	-47.1

Table 17 Menu of contracts using quadratic concave up SF function

Table 18 shows the result obtained by using the quadratic SF function shown above. Since all the DSO/regulator ratios in the tables are higher than 100, the quadratic SF are lower than linear SF function in all cases, hence the magnitudes of efficiency incentives given to DSOare lower when quadratic SF function was used. At DSO/regulator ratio above 100, the reward in case of cost saving and penalty in case of higher actual expenditure than forecast is lower using menu of contracts with the quadratic SF function compare to that using linear SF function.

Quadratic concave up SF function	Reference	Inflated DSO estimation	Actual expenditure lower than forecast	Actual expenditure higher than forecast
Regulator's estimate % of penetration	50.00%	50.00%	50.00%	50.00%
DSO's estimate % of penetration	60.00%	70.00%	60.00%	60.00%
Actual % of penetration	60.00%	60.00%	50.00%	70.00%
DSO/Regulator ratio	144.5	182.7	144.5	144.5
Sharing factor (%)	35.2%	25.7%	35.2%	35.2%
Additional income (%)	-6.9	-15.1	-6.9	-6.9
Allowed expenditure	117.8	133.1	117.8	117.8
Actual ratio	144.5	144.5	100.0	182.7
Actual efficiency incentive	-9.4	-2.9	6.3	-22.8
Final remuneration	128.2	126.5	99.4	153.0
Reward/Penalty	**-16.3**	**-18.1**	**-0.6**	**-29.8**

Table 18 Table of comparison using quadratic concave up SF function

Inflated DSO's forecast cost

Table 19 and Figure 21 show the penalty given when DSO inflates the ex-ante forecast cost at different level, keeping regulator's forecast and actual expenditure 50% and 60% respectively, which makes the actual ratio to be 144.5. The penalty that is imposed on DSO when using quadratic SF function is lower than with linear SF function, because of the lower quadratic SF. Furthermore, with higher DSO's estimated cost and higher DSO/regulator ratio, the quadratic SF decreases at a slower rate. With the quadratic SF function, the penalty increases with DSO/regulator ratio but at decreasing rate.

DSO's estimate % of penetration	70.00%	80.00%	90.00%
DSO/Regulator ratio	182.7	238.5	288.5
Linear SF function	-19.2	-26.6	-38.5
Quadratic SF function	-18.1	-23.5	-26.3

Table 19 Reward/penalty at different inflated forecast

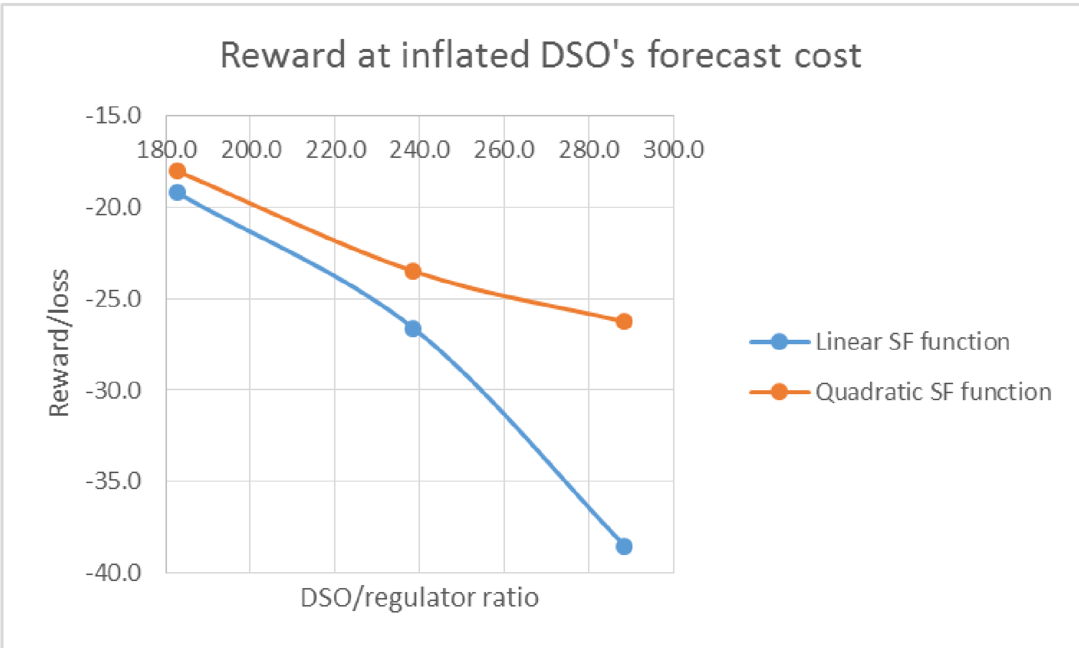

Figure 21 Reward/penalty at different inflated forecast

Actual expenditure lower than forecast

Table 20 and Figure 22 show the outcome of cost reduction by DSO by keeping regulator'sand DSO's estimations to be 50% and 60% respectively, which makes the DSO/regulator ratio to be 144.5. The more the saving made by DSO, the higher the reward they will earn. In this case, the DSO/regulator ratio remain constant, so as the sharing factor. Since DSO/regulator ratio is higher than 100, the quadratic SF is lower than linear SF, and hence the reward is lower in the case using quadratic SF.

Actual % of penetration	30.00%	40.00%	50.00%
Actual ratio	0.17	19.4	100
Linear SF function	41.5	33.6	0.5
Quadratic SF function	34.5	27.7	-0.6

Table 20 Reward/penalty at different level of cost reduction

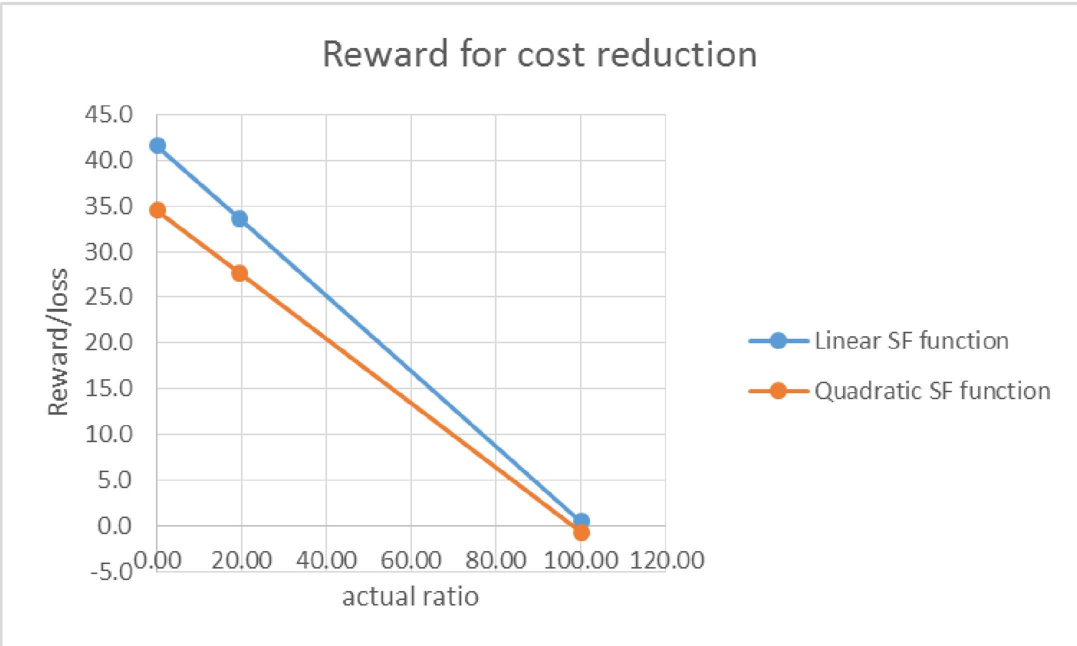

Figure 22 Reward/penalty at different level of cost reduction

Actual expenditure higher than forecast

The Table 21 and Figure 23 show the outcome when DSO spend higher than expected, keeping the regulator's and DSO's estimations at 50% and 60% respectively, which makes the DSO/regulator ratio to be 144.5. The DSO/regulator ratio remains the same and thus the SF is constant also. Since DSO/regulator ratio is higher than 100, the quadratic SF is lower than linear SF, and thus the losses is lower in the case using quadratic SF.

Actual % of penetration	70.00%	80.00%	90.00%
Actual ratio	182.7	238.5	288.5
Linear SF function	-33.5	-56.4	-76.9
Quadratic SF function	-29.8	-49.4	-67.0

Table 21 Reward/penalty at different level of cost overrun

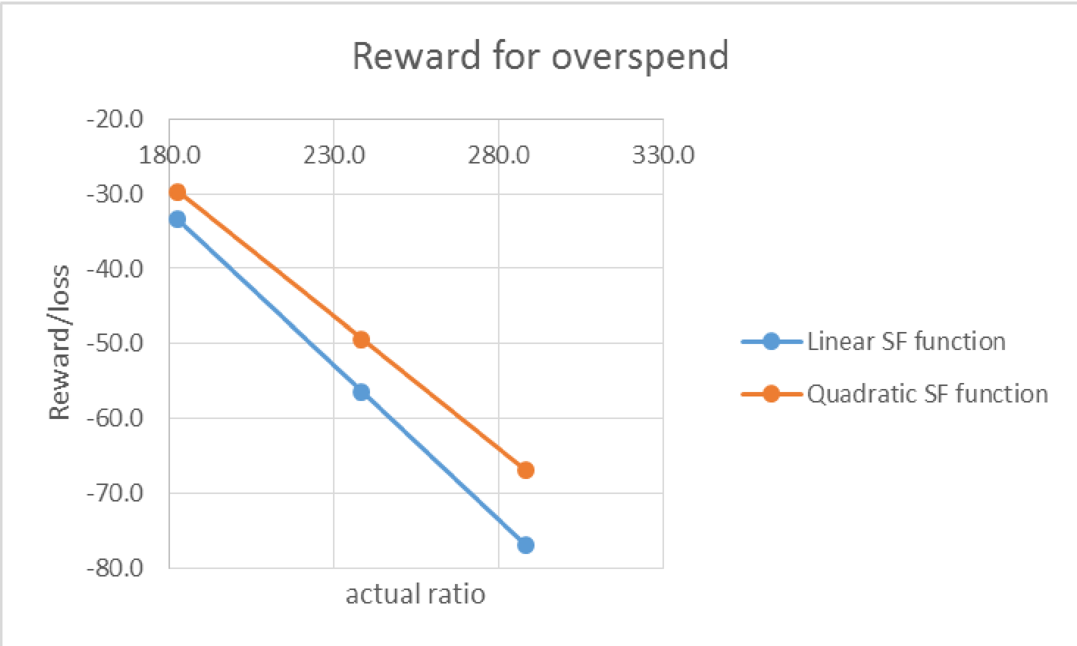

Figure 23 Reward/penalty at different level of cost overrun

6.3 Linear Upward and Downward Asymmetry vs Linear

A linear SF function which is used as reference and two linear upward asymmetry SF functions at different actual expenditure is shown in the Figure 24. Figure 25 shows a linear SF function which is used as reference and two linear downward asymmetry SF function at different actual expenditure. These figures show how the asymmetry SF varies around the reference SF at different actual expenditure. Compared to the SF using linear function, the upward asymmetry SF is lower when saving is larger and higher when overspending is larger while in the downward asymmetry function, SF is higher when saving is larger and lower when overspending is larger.

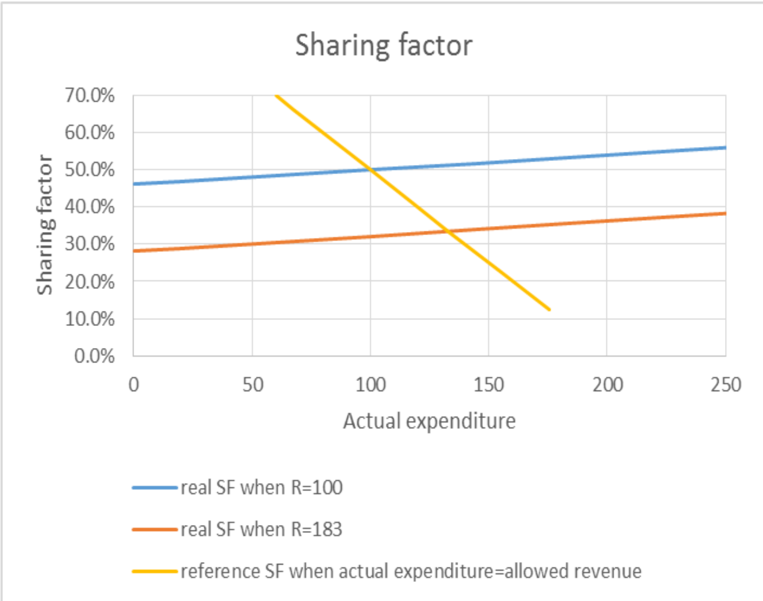

Figure 24 Linear upward asymmetry: $SF_{reference}$=0.5 at R=100, SF_{slope}=-0.002, ROC=0.004

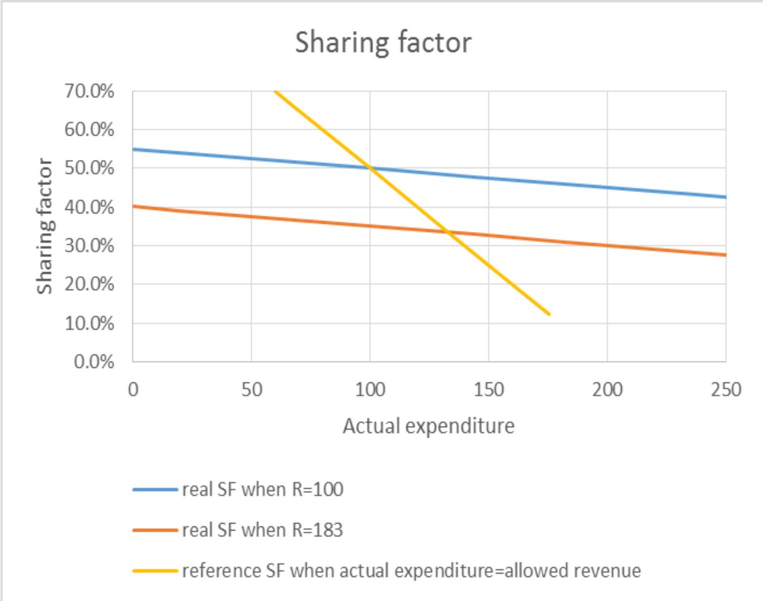

Figure 25 Linear downward asymmetry: $SF_{reference}$=0.5 at R=100, SF_{slope}=-0.002, ROC=-0.0005

Figure 26 and Figure 27 show the SF at different DSO/regulator ratio when using linear function, upward or downward asymmetry function at very low actual cost, and upward or downward asymmetry function at very high actual cost. In the upward asymmetry SF function, in case of higher actual expenditure than allowed revenue, the SF is higher than that in linear SF; in case of lower actual expenditure than allowed revenue, the SF is lower than that in linear SF. The situation is opposite in a downward asymmetry SF function.

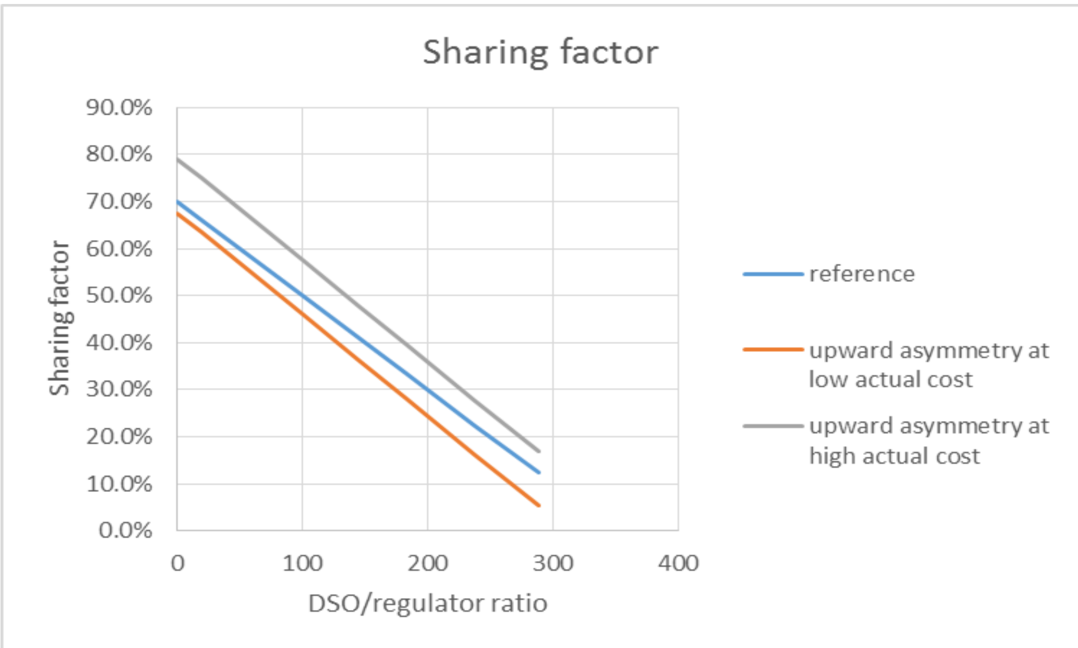

Figure 26 Linear upward asymmetry SF function: $SF_{reference}$=0.5 at R=100, SF_{slope}=-0.002, ROC=0.0004; Linear SF function: $SF_{reference}$=0.5 at R=100, SF_{slope}=-0.002

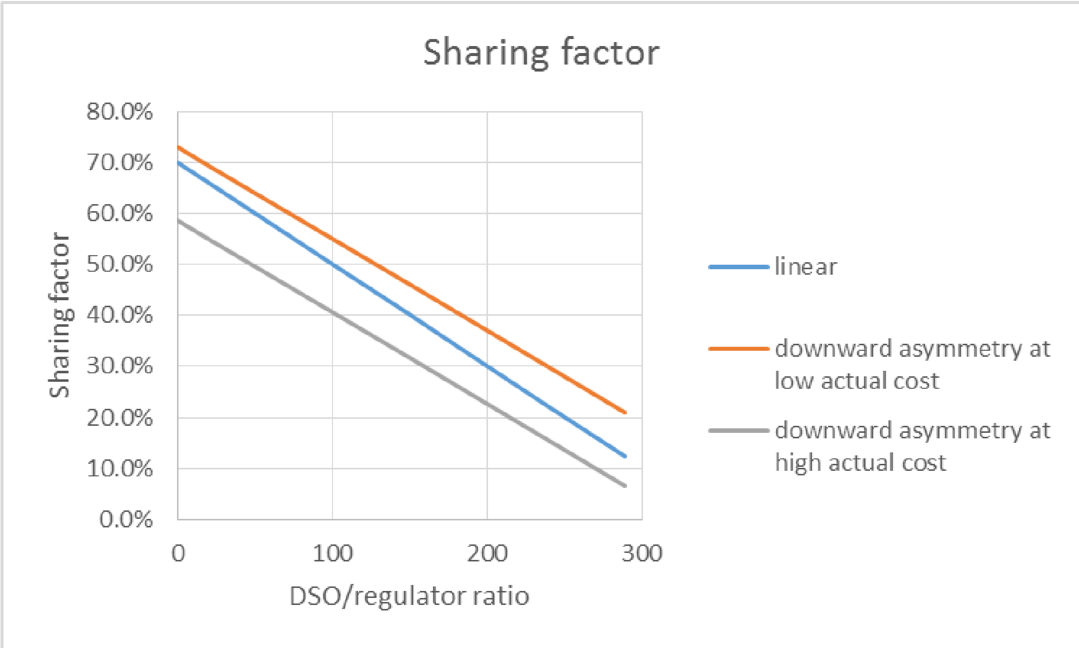

Figure 27 Linear downward asymmetry SF function: $SF_{reference}$=0.5 at R=100, SF_{slope}=-0.002, ROC=-0.0005; Linear SF function: $SF_{reference}$=0.5 at R=100, SF_{slope}=-0.002

With these SF functions, menus of contracts in Table 22 and Table 23 are obtained. Table 24 and Table 25 show the outcome when using these SF functions in different cases.

DSO/Regulator ratio	0.2	19.4	100.0	144.5	182.7	238.5	288.5
Allowed revenues	60.1	67.8	100.0	117.8	133.1	155.4	175.4
Additional income	19.5	16.7	2.5	-7.0	-16.1	-30.9	-45.7
0.2	60.0	59.6	48.4	35.8	21.3	-5.9	-36.4
19.4	47.3	47.7	40.2	29.6	16.8	-8.0	-36.3
100.0	-9.1	-5.0	2.5	0.2	-5.4	-19.8	-38.7
144.5	-42.4	-36.4	-20.6	-18.3	-20.0	-28.5	-42.3
182.7	-72.3	-64.6	-41.6	-35.4	-33.7	-37.3	-46.6
238.5	-118.1	-107.9	-74.4	-62.4	-55.8	-52.2	-55.1
288.5	-161.2	-148.7	-106.0	-88.8	-77.7	-67.6	-64.7

Table 22 Menu of contracts using linear upward asymmetry SF function

DSO/Regulator ratio	0.2	19.4	100.0	144.5	182.7	238.5	288.5
Allowed revenues	60.1	67.8	100.0	117.8	133.1	155.4	175.4
Additional income	21.7	18.1	2.5	-6.6	-14.6	-26.7	-38.0
0.2	65.4	65.1	57.4	48.7	38.7	19.9	-1.1
19.4	50.9	51.2	46.0	38.7	29.9	12.8	-6.7
100.0	-5.5	-2.7	2.5	0.9	-3.0	-12.9	-25.9
144.5	-33.9	-29.7	-18.8	-17.2	-18.4	-24.3	-33.8
182.7	-56.6	-51.3	-35.4	-31.1	-30.0	-32.5	-38.9
238.5	-87.3	-80.2	-57.2	-48.9	-44.3	-41.8	-43.8
288.5	-112.1	-103.5	-74.0	-62.1	-54.5	-47.6	-45.6

Table 23 Menu of contracts using linear downward asymmetry SF function

Linear upward asymmetry SF function	Reference	Inflated DSO estimation	Actual expenditure lower than forecast	Actual expenditure higher than forecast
Regulator's estimate % of penetration	50.00%	50.00%	50.00%	50.00%
DSO's estimate % of penetration	60.00%	70.00%	60.00%	60.00%
Actual % of penetration	60.00%	60.00%	50.00%	70.00%
DSO/Regulator ratio	144.5	182.7	144.5	144.5
Sharing factor (%)	42.2%	33.9%	40.4%	43.7%
Additional income (%)	-7.0	-16.1	-7.0	-7.0
Allowed expenditure	117.8	133.1	117.8	117.8
Actual ratio	144.5	144.5	100.0	182.7
Actual efficiency incentive	-11.3	-3.9	7.2	-28.4
Final remuneration	126.3	124.6	100.2	147.4
Reward/Penalty	**-18.3**	**-20.0**	**0.2**	**-35.4**

Table 24 Table of comparison using linear upward asymmetry SF function

Linear downward asymmetry SF function	Reference	Inflated DSO estimation	Actual expenditure lower than forecast	Actual expenditure higher than forecast
Regulator's estimate % of penetration	50.00%	50.00%	50.00%	50.00%
DSO's estimate % of penetration	60.00%	70.00%	60.00%	60.00%
Actual % of penetration	60.00%	60.00%	50.00%	70.00%
DSO/Regulator ratio	144.5	182.7	144.5	144.5
Sharing factor (%)	39.8%	32.9%	42.0%	37.8%
Additional income (%)	-6.6	-14.6	-6.6	-6.6
Allowed expenditure	117.8	133.1	117.8	117.8
Actual ratio	144.5	144.5	100.0	182.7
Actual efficiency incentive	-10.6	-3.8	7.5	-24.6
Final remuneration	127.3	126.2	100.9	151.6
Reward/Penalty	**-17.2**	**-18.4**	**0.9**	**-31.1**

Table 25 Table of comparison using linear downward asymmetry SF function

Inflated DSO's forecast cost

Table 26 and Figure 28 show the outcome when DSO inflates the ex-ante cost estimation at different rate, assuming regulator's estimation and actual cost are 50% and 60% respectively, which makes the actual ratio to be 144.5. When DSO inflates the cost, DSO gets higher penalty in upward asymmetry SF function than that using linear SF function, this is because at the same DSO/regulator ratio, the sharing factor for cost saving is lower in the upward asymmetry SF function. The sharing portion that they get from cost saving is lower. In the case of using a downward asymmetry SF function, when DSO inflate the cost, the loss that DSO get is less than that using linear SF function, this is because at the same DSO/regulator ratio, the sharing factor for cost saving is higher in the asymmetry SF function and the portion that they can get from the deviation of actual cost form allowed revenue is higher. However, if the real cost is provided ex-ante, the reward (penalty) that the DSO can get will be higher (lower).

DSO's estimate % of penetration	70.00%	80.00%	90.00%
DSO/Regulator ratio	182.7	238.5	288.5
Linear SF function	-19.2	-26.6	-38.5
Upward asymmetry SF function	-20.0	-28.5	-42.3
Downward asymmetry SF function	-18.4	-24.3	-33.8

Table 26 Reward/penalty at different inflated forecast

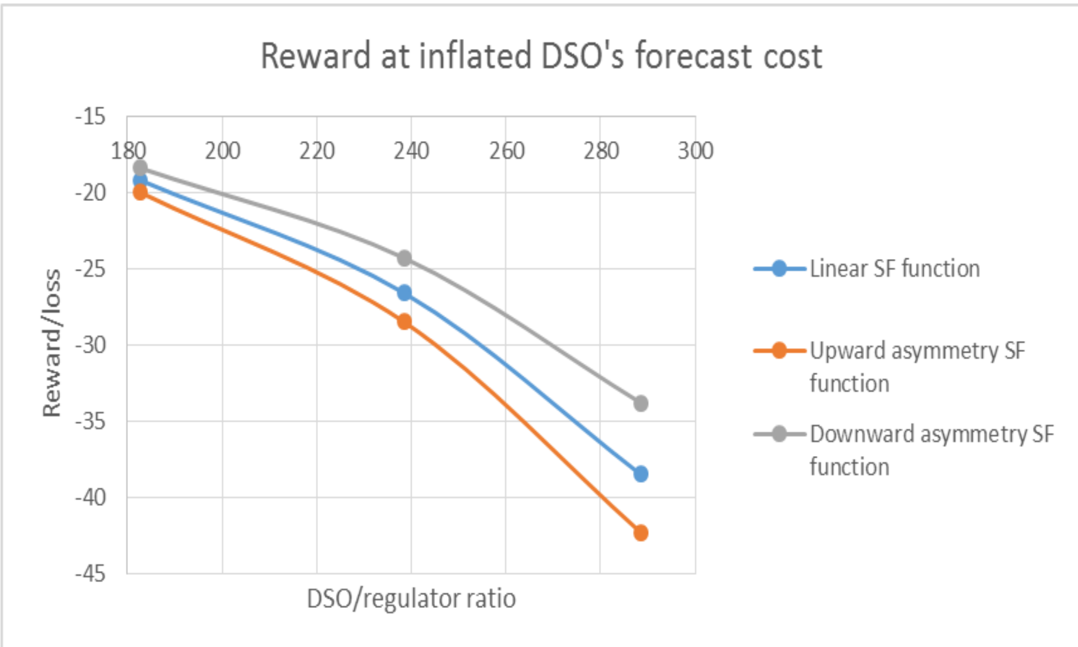

Figure 28 Reward/penalty at different inflated forecast

Actual expenditure lower than forecast

Table 27 and Figure 29 show the outcome when DSO spends lower than the forecast cost, assuming regulator's and DSO's estimations are 50% and 60% respectively, which makes the DSO/regulator ratio to be 144.5. In all the SF functions, reward increases with cost reduction. In the upward asymmetry SF function, outperformance is rewarded at lower degree. Thus, reward for cost saving is lower using upward asymmetry SF function. Furthermore, in upward asymmetry SF function, the sharing factor gets lower with larger cost saving. Hence, when the cost reduced becomes larger, the rate of increase in reward gets slower and reward approaches a limit. On the other hand, outperformance is rewarded better in downward asymmetry SF function. The reward for cost saving is higher using a downward asymmetry SF function. In addition to that, in downward asymmetry SF function, the SF gets higher with larger cost saving. Hence, as the cost reduction becomes larger, the rate of increase in reward gets faster also.

Actual % of penetration	30.00%	40.00%	50.00%
Actual ratio	0.17	19.4	100
Linear SF function	41.5	33.6	0.5
Upward asymmetry SF function	35.8	29.6	0.2
Downward asymmetry SF function	48.7	38.7	0.9

Table 27 Reward/penalty at different level of cost reduction

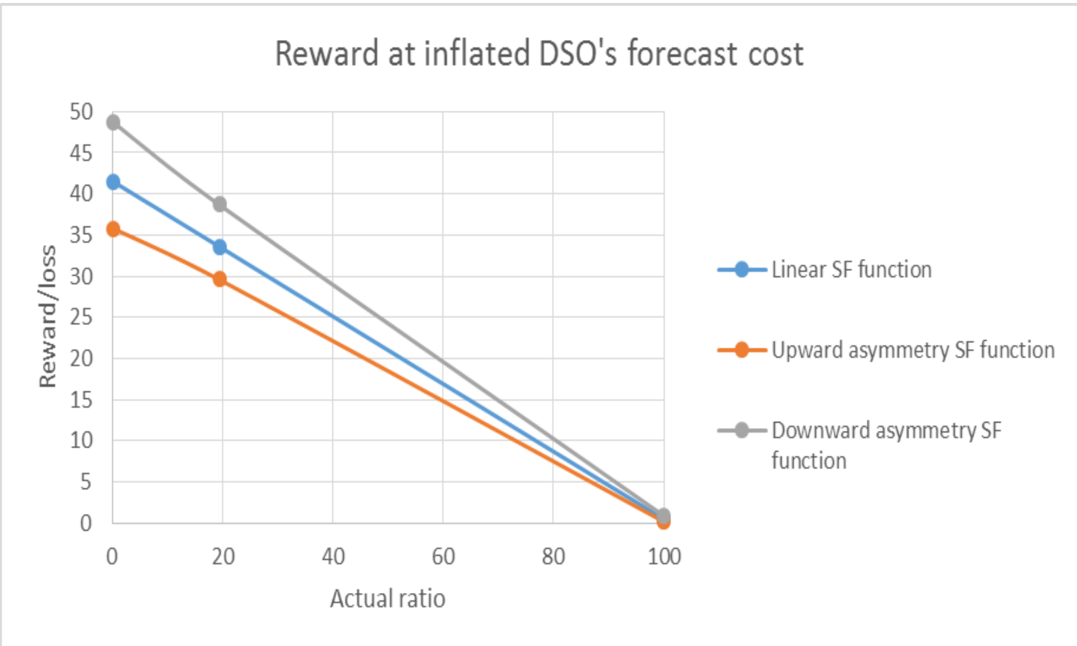

Figure 29 Reward/penalty at different level of cost reduction

Actual expenditure higher than forecast

Table 28 and Figure 30 show the outcome when DSO spend cost higher than forecast, assuming regulator's and DSO's estimations are 50% and 60% respectively, which makes the DSO/regulator ratio to be 144.5. In all SF functions, loss increases with cost overrun. In the upward asymmetry SF function, underperformance is penalized more severely. Thus, losses when cost overrun are higher in using upward asymmetry SF function. In addition to that, in upward asymmetry SF function, the SF gets higher with larger cost overrun. Hence, as the cost overrun gets larger, the rate of increase in penalty gets faster as well. On the other hand, in the downward asymmetry SF function, underperformance is penalized less severely. Thus, losses when cost overrun are lower using downward asymmetry SF function. In addition to that, in downward asymmetry SF function, the sharing factor gets lower with larger cost overrun. Hence, when cost overrun becomes larger, the rate of increase in penalty gets slower and approaches a limit.

Actual % of penetration	70.00%	80.00%	90.00%
Actual ratio	182.7	238.5	288.5
Linear SF function	-33.5	-56.4	-76.9
Upward asymmetry SF function	-35.4	-62.4	-88.8
Downward asymmetry SF function	-31.1	-48.9	-62.1

Table 28 Reward/penalty at different level of cost overrun

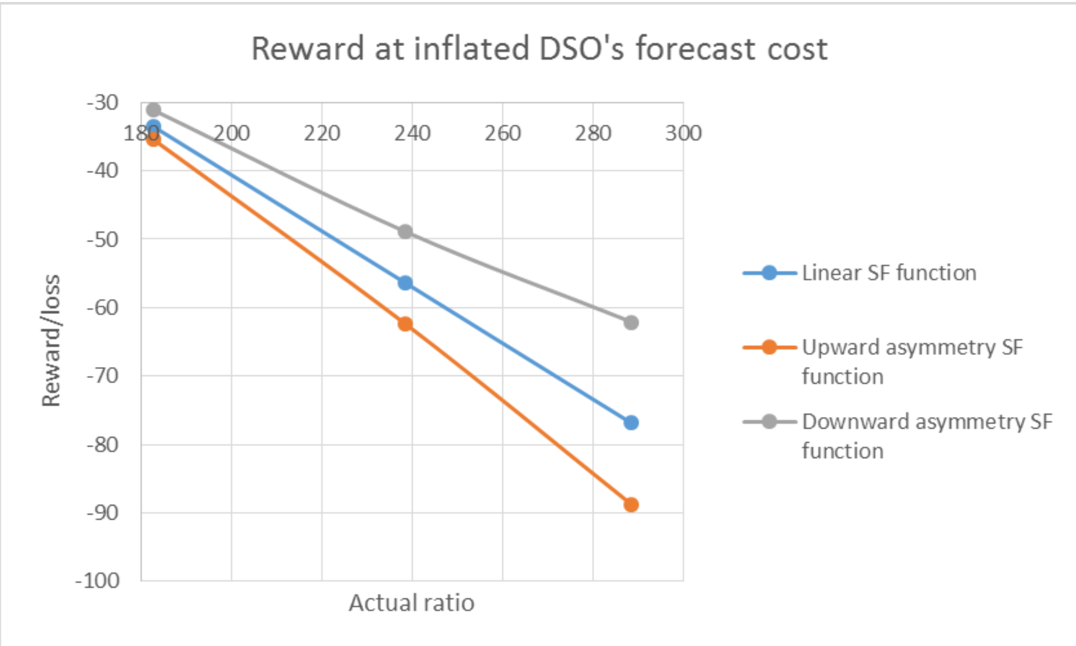

Figure 30 Reward/penalty at different level of cost overrun

Figure 31 provides a clearer view about how the reward and penalty changes with actual expenditure, comparing linear SF function to upward and downward asymmetry SF function.

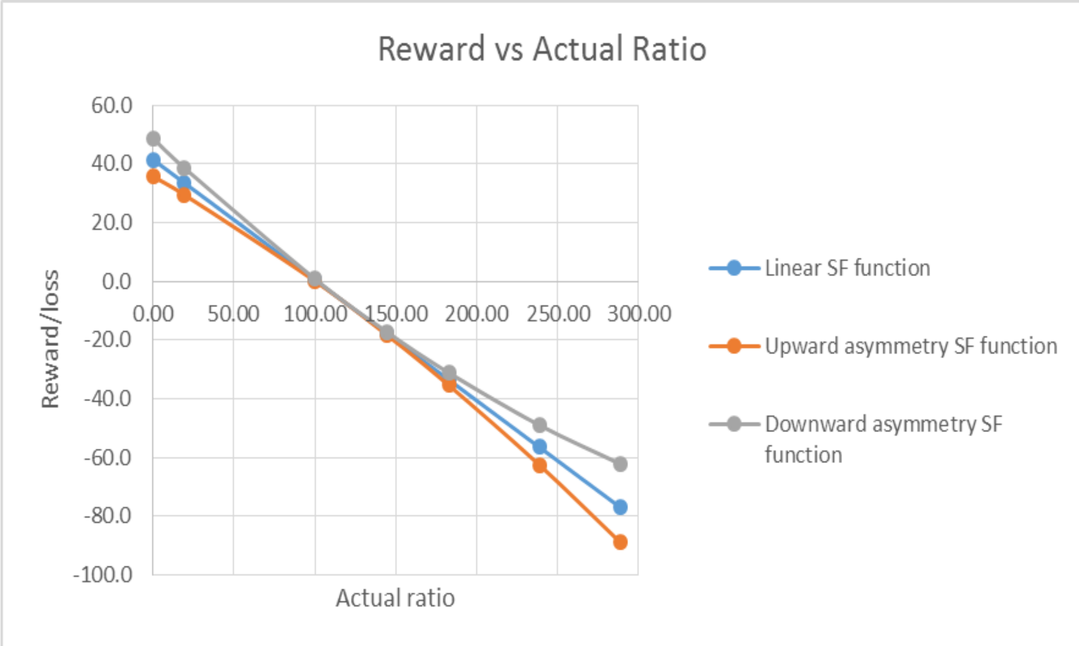

Figure 31 Reward at different actual expenditure

6.4 Implications of the SF Functions in Menu of Contracts

From the comparisons, the characteristics of the menu of contract constructed by differentSF functions are known. It is important to analyse the implications of these characteristicssothat the usages of these menus of contracts can be further explored. From the result of analyses, regulator will be able to choose the most suitable menu of contracts based on the desired requirements. The SF functional forms introduced here can be used to achieve different requirements desired in the remuneration scheme. Careful tuning of the parameters usedin the SF functions makes the menu of contracts more flexible in terms of having different rate of change of SF with DSO's estimated cost and with actual expenditure.

With a concave down SF function, when DSO inflates the ex-ante forecast cost, the reward decreases with the amount inflated at a faster rate compared to linear SF. This implies that the DSOs are very discouraged from inflating the cost as the penalty can go very high. This menu of contracts is useful especially when the regulator has high level of confidence in the benchmark cost provided and the regulator wants to avoid any possible strategic behaviour of DSO by imposing increasingly heavier penalty with inflated forecast cost. All the concave down SF functions show the same characteristics in menu of contracts, that is, increasing rate of change in reward with higher DSO's forecast. However, the flexibility in adjusting the rate of change of SF function is better with a cubic function compared to a quadratic function. The SF at different R can be set by carefully tuning the coefficient of different R's order and the changes will be reflected at higher or lower range of R. In comparison, adjusting the coefficient of R^3 changes the function more at higher R and adjusting the coefficient of R changes the function more at lower R. A piecewise function with three sections is used in this thesis. It is possible to have higher flexibility with the changes in slope when more sections are used but this will increase the complexity of the function.

On the other hand, with concave up SF function, when the DSO ex-ante forecast cost gets higher, the reward decreases with the forecasted cost at a slower rate compared to that of linear SF. This implies that the attitude towards DSO who submits higher forecast cost is milder. This can be due to unconfident benchmark cost or high uncertainty about the future. A piecewise function provides flexibility in adjusting the slope across DSO/regulator ratio. Higher flexibility can be achieved with more sections in the piece wise function but at the same time, the function will become more complex.

Upward asymmetry SF function shows that when the DSO/regulator ratio is constant, the penalty for overspending is higher and reward for cost saving is lower. In case the DSOs underperform, high penalty will be imposed. In case they outperform and have saved cost, a reward will be given but more limited. In fact, the reward for cost saving actually approaches a limit when the actual cost becomes less and less. This situation mainly implies that DSOs are strongly discourage from spending higher than the forecast. This asymmetricity can be particularly suitable to remunerate DSO in investments with high certainty and lower risk.

In contrary to the upward asymmetry SF function, the use of downward asymmetry SF function shows that when the DSO/regulator ratio is constant, there is higher reward for cost saving and less penalty for overspending. In case the DSOs outperformance and have saved cost, high reward will be given. On the other hand, in the case that they overspend, there will still be penalty but it is more limited. The penalty for overspending actually approaches a limit when the actual cost becomes higher and higher. This situation implies that regulator is encouraging DSOs to invest by not penalizing them heavily when they spend higher than forecast. This type of asymmetricity can be useful in remunerating DSO in an investment with very high uncertainty and risk.

The implications of the concave functions and asymmetry functions have been discussed separately. The combine use of concave function and asymmetry function in a SF function may produce a menu of contract which is more specific. For example, in case where regulator has high confidence with the benchmark cost in an investment with low uncertainty, a sharing factor which combines a concave down function and a linear upward asymmetry function can be used in the menu of contract to take the advantage from both functions. Hence, the flexible use of different SF functions will enable a menu of contracts to adapt to the needs of regulator easier.

The objective of this thesis is to assess the incentive properties of different designs of menu of contracts during network investment. The variation in their properties is achieved by developing new designs of sharing factor functions to build an incentive-compatible menu of contracts. In order to assess how the alternative designs performed, RNM is used as a tool to estimate the network expansion expenditures needed at varying levels of PV penetration. The resulted investment costs generated from RNM at different levels of PV penetration are used as the regulator's forecast, DSO's forecast and actual expenditure in the menu of contracts. The outcomes obtained from these menus of contract are compared and analysed under different scenarios. The analyses have shown that the menus of contracts with different SF functional forms can be used by regulator to achieve different requirements in remuneration scheme.

In this thesis, the result of RNM is used to assess the incentive properties of menu of contracts constructed using the new designs of SF functions, which are concave down SF function, concave up SF function, linear upward asymmetry SF function and linear downward asymmetry SF function. When RNM is used to estimate the cost of investment needed in network expansion, regulator can have reliable information about investment cost needed by DSO and hence the problem of information asymmetry between regulator and DSO is avoided. At the same time, the problem of having benchmark error in menu of contracts can be mitigated by applying the output of RNM into menu of contracts.

With the benchmark cost of high confidence level at hand, regulator can encourage DSO to submit the real estimated cost by introducing a menu of contracts with incentive power which decreases rapidly when DSO inflates the forecast cost. By doing so, regulator can reduce the reward or increase the penalty to DSO at an increasingly faster rate with the amount DSO inflates. A concave down SF which has increasingly negative slope with DSO/regulator ratio has been designed to achieve this characteristic in menu of contracts. Increasing rate of decrease in SF with DSO/regulator ratio will reflect the rate of decrease in reward when DSO inflates the forecast cost. The flexibility in tuning the downward slope of a cubic or linear piecewise function enables regulator to adjust the incentive power to what is desired. On the other hand, if regulator does not have reliable information and cost forecast, the uncertainties about expenditure and possibility of having benchmark error are high. In this case, a menu of contracts with concave up SF, which has its SF function decreases with DSO/regulator ratio at decreasing rate can be a good choice.

Once the DSO submitted the ex-ante forecast and the DSO/regulator ratio is fixed, the regulator can look further into how outperformance of DSO should be rewarded and how underperformance should be penalized. When regulator and consumers favour one outcome more than the other, an asymmetric SF function can be used. An upward asymmetry SF function changes positively with actual expenditure while a downward asymmetry SF function changes negatively with actual expenditure. The upward asymmetry SF function has lower SF when actual expenditure is low and higher SF when actual expenditure is high. Underperformance is penalized at higher rate while outperformance is rewarded at lower rate. This asymmetry SF function can be used when regulators dislike overspending more than they like cost-saving. For example, in activities with lower difficulty and limited risks, DSO is expected to keep with the standard and do not overspend. By having increasing SF with actual expenditure, DSO will have to bear higher portion of the cost in case of cost overrun, instead of having consumers paying for it. This ensures that the benefits of consumers are protected and also strongly discourage DSO from overspending. When DSO manage to save cost, reward will be given. However, with decreasing SF with actual expenditure, the portion that the DSO can get becomes lower with higher cost saved.

A downward asymmetry SF function has higher SF at low actual expenditure and lower SF at high actual expenditure. Outperformance is rewarded at higher rate while underperformance is penalized at lower rate. In the situation where investment has high risk and high difficulty, but its implementation is more appreciated than having cost reduction, the downward asymmetry SF function can be used. An example of this situation will be the investment in new technology by DSO. In order to encourage DSO to invest, SF decreases when DSO overspend and increases when there is cost saving. Thus, the risk of DSO in case of overspending will be lower but the consumers will need to take higher risk because they will need to bear a larger portion of the cost. On the other hand, in case of cost saving, DSO will be the one who get higher portion of saving as a reward for efficiency gain.

In conclusion, the introduction of different designs of SF enables the regulator to construct the menu of contracts according to requirements. The choice can be done by looking at two aspects, firstly, whether the confidence level of regulator towards its benchmark cost is high and secondly, whether it is desirable to have an asymmetric incentive strength for outperformance and underperformance. The combination of RNM and menu of contracts helps in reducing benchmark error and make the menu of contracts more realistic. The characteristics of the investment project, for example, the risk level, difficulty and consumers' expectation can also influence the regulator's decision of SF function used.

The characteristics of the concave functions and asymmetry functions and their implications have been analysed separately. In order to take advantage from both type of functions and to make the menu of contracts more specific, it might be useful to combine these functions. For instance, an asymmetry SF function which is based on a concave down SF function can be used when the regulator has high confidence with the benchmark cost in an investment with low uncertainty. More studies can be done in order to assess the combined benefits. In addition to that, in the profit-sharing menu of contracts, investment cost is the only criteria that has been taken into account for remuneration. Other than investment cost, regulator can also consider more criteria when designing a remuneration scheme, for example, the quality of deliverables and delivery timeline. Minimum quality standard and quality's benchmark can be set by regulator and extra rewards or penalty can be given based on the final quality of deliverables. The remuneration can also be affected by the deviation of actual delivery timeline from the allowed delivery timeline. However, the remuneration scheme will become more complex when more criteria are being considered. Further research can be carried so that the DSO can be remunerated more appropriately by taking in all possible variables.

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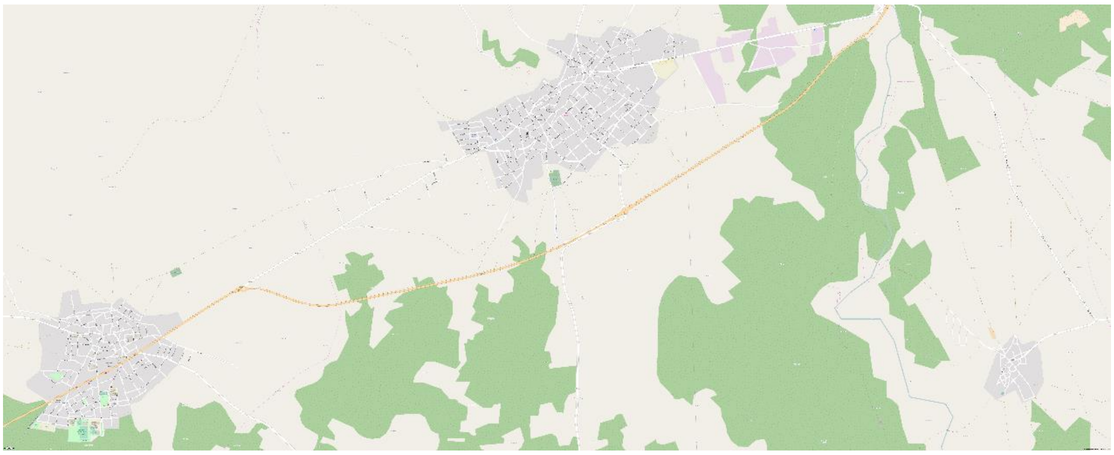
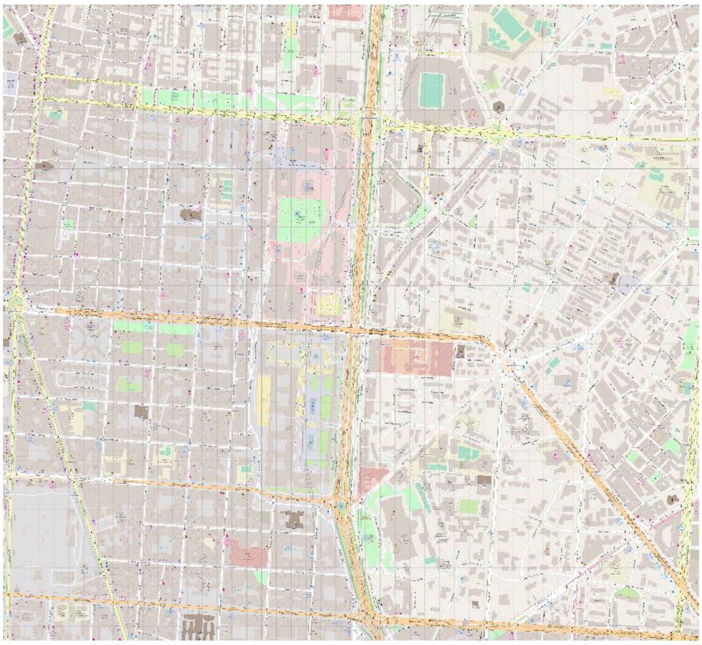
Appendix A: Actual street maps used for image processing

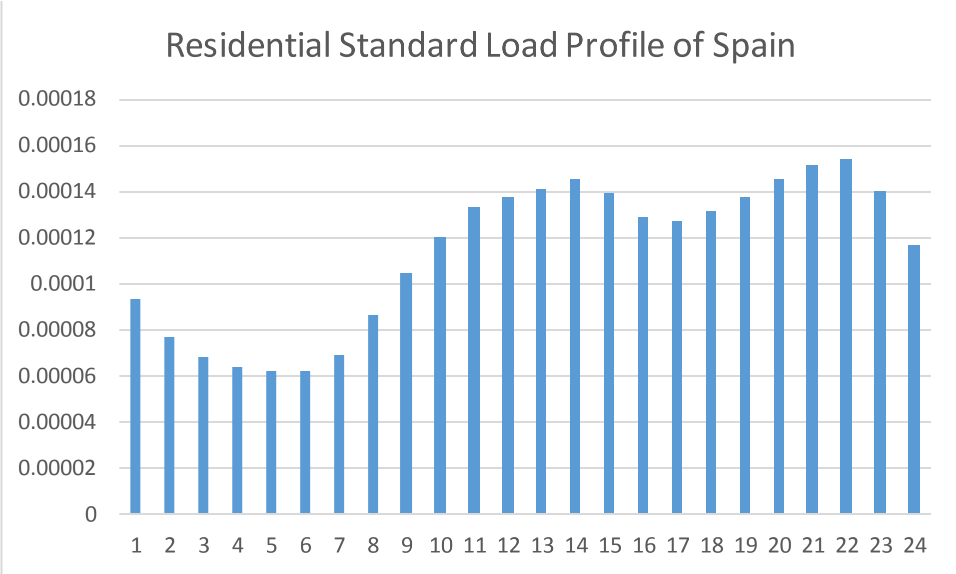


Actual street map used for image processing in rural area

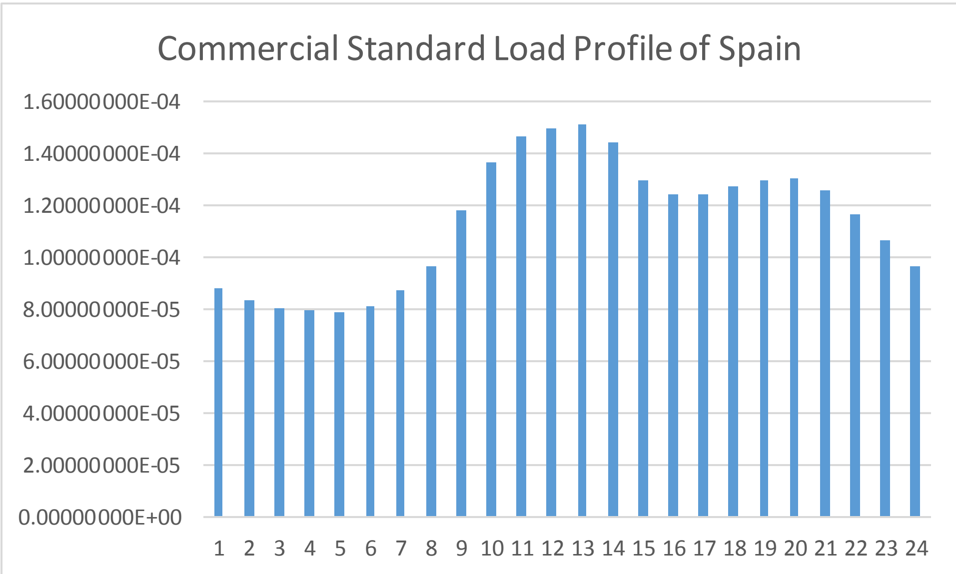


Actual street map used for image processing in urban area

Appendix B: Standard load profiles for residential and commercial



Residential standard load profile



Commercial standard load profile

Appendix C: Calculation of additional income for quadratic sharing factor function

Calculation of additional income with quadratic sharing factor function:

$$\begin{aligned} Reward &= (AR - E) \cdot SF + AI \\ &= (\sigma_1 - w\sigma_1 + \alpha_1)R^3 + (100w\sigma_1 + \sigma_2 - w\sigma_2 - E\sigma_1 + \alpha_2)R^2 \\ &\quad + (100w\sigma_2 + \sigma_3 - w\sigma_3 - E\sigma_2 + \alpha_3)R + 100w\sigma_3 + \alpha_4 - E\sigma_3 \end{aligned}$$

The reward received by firm is maximum when the first derivative of Reward with respect to R is equal to zero.

$$\begin{aligned} \frac{dReward}{dR} &= 3(\sigma_1 - w\sigma_1 + \alpha_1)R^2 + 2(100w\sigma_1 + \sigma_2 - w\sigma_2 - E\sigma_1 + \alpha_2)R + 100w\sigma_2 + \sigma_3 \\ &\quad - w\sigma_3 - E\sigma_2 + \alpha_3 \\ &= 0 \end{aligned}$$

This should happen whenever the actual expenditure is equal to R. Hence, R is substituted with actual expenditure.

$$(\sigma_1 - 3w\sigma_1 + 3\alpha_1)E^2 + (200w\sigma_1 + \sigma_2 - 2w\sigma_2 + 2\alpha_2)E - 100w\sigma_2 + \sigma_3 - w\sigma_3 + \alpha_3 = 0$$

This equation should be true for all the values of actual expenditure. For this condition to be satisfied, the factors which are multiplied by actual expenditure raised to any power should be equal to zero.

Therefore,

$$\alpha_1 = \frac{3w\sigma_1 - \sigma_1}{3}$$

$$\alpha_2 = \frac{2w\sigma_2 - \sigma_2 - 200w\sigma_1}{2}$$

$$\alpha_3 = w\sigma_3 - 100w\sigma_2 - \sigma_1$$

α_4 will not affect the incentive compatibility of the menu matrix and hence, the regulator is free to determine α_4 by taking into account the overall profitability of the menu matrix desired. By equating the equation of additional income to the reference value of additional income when R equals to certain value, α_4 can be determined.

$$\alpha_4 = AI_{reference} - \alpha_1 R_{reference}{}^3 - \alpha_2 R_{reference}{}^2 - \alpha_3 R_{reference}$$

Appendix D: Calculation of additional income for cubic sharing factor function

Calculation of additional income with cubic sharing factor function:

$$
\begin{aligned}
Reward &= (AR - E) \cdot SF + AI \\
&= (\sigma_1 - w\sigma_1 + \alpha_1)R^4 + (100w\sigma_1 + \sigma_2 - w\sigma_2 - E\sigma_1 + \alpha_2)R^3 \\
&\quad + (100w\sigma_2 + \sigma_3 - w\sigma_3 - E\sigma_2 + \alpha_3)R^2 \\
&\quad + (100w\sigma_3 + \sigma_4 - w\sigma_4 - E\sigma_3 + \alpha_4)R + 100w\sigma_4 - E\sigma_4 + \alpha_5
\end{aligned}
$$

The reward received by firm is maximum when the first derivative of Reward with respect to R is equal to zero.

$$
\begin{aligned}
\frac{dReward}{dR} &= 4(\sigma_1 - w\sigma_1 + \alpha_1)R^3 + 3(100w\sigma_1 + \sigma_2 - w\sigma_2 - E\sigma_1 + \alpha_2)R^2 \\
&\quad + 2(100w\sigma_2 + \sigma_3 - w\sigma_3 - E\sigma_2 + \alpha_3)R + 100w\sigma_3 + \sigma_4 - w\sigma_4 - E\sigma_3 \\
&\quad + \alpha_4 \\
&= 0
\end{aligned}
$$

This should happen whenever the actual expenditure is equal to R. Hence, R is substituted with actual expenditure, E.

$$
\begin{aligned}
&(\sigma_1 - 4w\sigma_1 + 4\alpha_1)E^3 + (300w\sigma_1 + \sigma_2 - 3w\sigma_2 + 3\alpha_2)E^2 \\
&\quad - (200w\sigma_2 + \sigma_3 - 2w\sigma_3 + 2\alpha_3)E + 100w\sigma_3 + \sigma_4 - w\sigma_4 + \alpha_4 = 0
\end{aligned}
$$

This equation should be true for all the values of actual expenditure. For this condition to be satisfied, the factors which are multiplied by actual expenditure raised to any power should be equal to zero.

Therefore,

$$
\begin{aligned}
\alpha_1 &= \frac{4w\sigma_1 - \sigma_1}{4} \\
\alpha_2 &= \frac{3w\sigma_2 - 300w\sigma_1 - \sigma_2}{3} \\
\alpha_3 &= \frac{2w\sigma_3 - 200w\sigma_2 - \sigma_3}{2} \\
\alpha_4 &= w\sigma_4 - 100w\sigma_3 - \sigma_4
\end{aligned}
$$

α_5 will not affect the incentive compatibility of the menu matrix and hence, the regulator is free to determine α_5 by taking into account the overall profitability of the menu matrix desired. By equating the equation of additional income to the reference value of additional income when R equals to certain value, α_5 can be determined.

$$
\alpha_5 = AI_{reference} - \alpha_1 {R_{reference}}^4 - \alpha_2 {R_{reference}}^3 - \alpha_3 {R_{reference}}^2 - \alpha_4 R_{reference}
$$

Appendix E: Calculation of additional income for linear asymmetry sharing factor function

Calculation of additional income with linear asymmetry sharing factor function:

$$
\begin{aligned}
Reward &= (allowed\ expenditure - actual\ expenditure) \cdot SF + AI \\
&= \left(SF_{slope} - ROC + 2 \cdot ROC \cdot w - SF_{slope} \cdot w - ROC \cdot w^2 + \alpha_1\right)R^2 \\
&\quad + \left(100 \cdot SF_{slope} \cdot w - 200 \cdot ROC \cdot w + 200 \cdot ROC \cdot w^2 - SF_{slope} \right. \\
&\quad \cdot R_{reference} + SF_{reference} + 2 \cdot ROC \cdot E + SF_{slope} \cdot R_{reference} \cdot w \\
&\quad \left. - SF_{reference} \cdot w - 2 \cdot ROC \cdot E \cdot w - SF_{slope} \cdot E + \alpha_2\right)R - 100 \cdot SF_{slope} \\
&\quad \cdot R_{reference} \cdot w + 100 \cdot SF_{reference} \cdot w + 200 \cdot ROC \cdot E \cdot w - 100^2 \cdot ROC \\
&\quad \cdot w^2 + SF_{slope} \cdot R_{reference} \cdot E - SF_{reference} \cdot E - ROC \cdot E^2 + \alpha_3
\end{aligned}
$$

The reward received by firm is maximum when the first derivative of Reward with respect to R is equal to zero.

$$
\begin{aligned}
\frac{dReward}{dR} &= 2(SF_{slope} - ROC + 2 \cdot ROC \cdot w - SF_{slope} \cdot w - ROC \cdot w^2 + \alpha_1)R \\
&\quad + 100 \cdot SF_{slope} \cdot w - 200 \cdot ROC \cdot w + 200 \cdot ROC \cdot w^2 - SF_{slope} \\
&\quad \cdot R_{reference} + SF_{reference} + 2 \cdot ROC \cdot E + SF_{slope} \cdot R_{reference} \cdot w \\
&\quad - SF_{reference} \cdot w - 2 \cdot ROC \cdot E \cdot w - SF_{slope} \cdot E + \alpha_2 \\
&= 0
\end{aligned}
$$

This should happen whenever the E is equal to R. Hence, R is substituted with actual expenditure.

$$
\begin{aligned}
&(SF_{slope} + 2 \cdot ROC \cdot w - 2 \cdot SF_{slope} \cdot w - 2 \cdot ROC \cdot w^2 + 2 \cdot \alpha_1)E + 100 \cdot SF_{slope} \cdot w \\
&\quad - 200 \cdot ROC \cdot w + 200 \cdot ROC \cdot w^2 - SF_{slope} \cdot R_{reference} + SF_{reference} \\
&\quad + SF_{slope} \cdot R_{reference} \cdot w - SF_{reference} \cdot w + \alpha_2 = 0
\end{aligned}
$$

This equation should be true for all the values of actual expenditure. For this condition to be satisfied, the factors which are multiplied by E should be equal to zero. Therefore,

$$
\begin{aligned}
\alpha_1 &= \frac{SF_{slope} \cdot (2w - 1) + 2 \cdot ROC \cdot w(w - 1)}{2} \\
\alpha_2 &= SF_{slope}\left(R_{reference} - 100w - R_{reference} \cdot w\right) + 200 \cdot ROC \cdot w(1 - w) \\
&\quad + SF_{reference}(w - 1)
\end{aligned}
$$

α_3 will not affect the incentive compatibility of the menu matrix and hence, the regulator is free to determine α_3 by taking into account the overall profitability of the menu matrix desired. By equating the equation of additional income to the reference value of additional income when R equals to certain value, α_3 can be determined.

$$\alpha_3 = AI_{reference} - \alpha_1 {R_{reference}}^2 - \alpha_2 R_{reference}$$

Appendix F: Parameters used for constructing a menu of contract with linear piecewise sharing factor function

Abbreviation	Descriptions	Equation/Constraint
AR	Allowed revenue	$w \bullet 100 + (1-w) \bullet R$
w	weightage given to the cost estimated by regulator	0 to 1
R	DSO forecast cost/regulator's benchmark	–

Abbreviation	Descriptions	Equation/Constraint
SF	Sharing factor	$(R-R_{ref}) \bullet SF_{slope} + SF_{ref}$
R_{ref}	R's reference point	–
SF_{slope}	Slope of SF across R	< 1
SF_{ref}	SF's reference value at R_{ref}	0 to 1

Abbreviation	Descriptions	Equation/Constraint
AI	Additional income	$\gamma + \alpha R + \beta R^2$
γ	Constant term in AI	$AI_{ref} - \alpha R_{ref} - \beta R_{ref}^2$
AI_{ref}	AI's reference value at R_{ref}	–
α	Coefficient of first order term in AI	$SF_{ref} \bullet (w-1) + SF_{slope} \bullet [R_{ref} \bullet (1-w) - 100w]$
β	Coefficient of second order term in AI	$SF_{slope} \bullet (w-0.5)$

Appendix G: Parameters used for constructing a menu of contract with quadratic sharing factor function

Abbreviation	Descriptions	Equation/Constraint
AR	Allowed revenue	$w \cdot 100+(1-w) \cdot R$
w	weightage given to the cost estimated by regulator	0 to 1
R	DSO forecast cost/regulator's benchmark	–

Abbreviation	Descriptions	Equation/Constraint
SF	Sharing factor	$\sigma_1 R^2+\sigma_2 R+\sigma_3$
$\boldsymbol{\sigma_1}$	Coefficient of second order term in SF.	< 1 produces a concave down SF function > 1 produces a concave up SF function
$\boldsymbol{\sigma_2}$	Coefficient of first order term in SF	$-2\sigma_1 \cdot R$
$\boldsymbol{\sigma_3}$	Constant term in SF	$SF_{ref} - \sigma_1 R_{ref}^2 - \sigma_2 R_{ref}$
$\mathbf{SF_{ref}}$	SF's reference value at R_{ref}	0 to 1
$\mathbf{R_{ref}}$	R's reference point	–

Abbreviation	Descriptions	Equation/Constraint
AI	Additional income	$\alpha_1 R^3+\alpha_2 R^2+\alpha_3 R+\alpha_4$
$\boldsymbol{\alpha_1}$	Coefficient of third order term in AI	$(3w\sigma_1-\sigma_1)/3$
$\boldsymbol{\alpha_2}$	Coefficient of second order term in AI	$(2w\sigma_2-\sigma_2-200w\sigma_1)/2$
$\boldsymbol{\alpha_3}$	Coefficient of first order term in AI	$w\sigma_3-100w\sigma_2-\sigma_1$
$\boldsymbol{\alpha_4}$	Constant term in AI	$AI_{ref}-\alpha_1 R^3-\alpha_2 R^2-\alpha_3 R$
$\mathbf{AI_{ref}}$	AI's reference value at R_{ref}	–

Appendix H: Parameters used for constructing a menu of contract with cubic sharing factor function

Abbreviation	Descriptions	Equation/Constraint
AR	Allowed revenue	$w \bullet 100+(1-w) \bullet R$
w	weightage given to the cost estimated by regulator	0 to 1
R	DSO forecast cost/regulator's benchmark	–

Abbreviation	Descriptions	Equation/Constraint
SF	Sharing factor	$\sigma_1 R^3+\sigma_2 R^2+\sigma_3 R+\sigma_4$
$\boldsymbol{\sigma_1}$	Coefficient of third order term in SF.	< 1 produces a concave down SF function
$\boldsymbol{\sigma_2}$	Coefficient of second order term in SF	0
$\boldsymbol{\sigma_3}$	Coefficient of first order term in SF.	< 1
$\boldsymbol{\sigma_4}$	Constant term in SF	$SF_{ref} - \sigma_1 R_{ref}^3 - \sigma_2 R_{ref}^2 - \sigma_3 R_{ref}$
$\mathbf{SF_{ref}}$	SF's reference value at R_{ref}	0 to 1
$\mathbf{R_{ref}}$	R's reference point	–

Abbreviation	Descriptions	Equation/Constraint
AI	Additional income	$\alpha_1 R^4+\alpha_2 R^3+\alpha_3 R^2+\alpha_4 R+\alpha_5$
$\boldsymbol{\alpha_1}$	Coefficient of fourth order term in AI	$(4w\sigma_1-\sigma_1)/4$
$\boldsymbol{\alpha_2}$	Coefficient of third order term in AI	$(3w\sigma_2-300w\sigma_1-\sigma_2)/3$
$\boldsymbol{\alpha_3}$	Coefficient of second order term in AI	$(2w\sigma_3-200w\sigma_2-\sigma_3)/2$
$\boldsymbol{\alpha_4}$	Coefficient of first order term in AI	$w\sigma_4-100w\sigma_3-\sigma_4$
$\boldsymbol{\alpha_5}$	Constant term in AI	$AI_{ref}-\alpha_1 R^4-\alpha_2 R^3-\alpha_3 R^2-\alpha_4 R$
$\mathbf{AI_{ref}}$	AI's reference value at R_{ref}	–

Appendix I: Parameters used for constructing a menu of contract with linear asymmetry sharing factor function

Abbreviation	Descriptions	Equation/Constraint
AR	Allowed revenue	$w \bullet 100 + (1-w) \bullet R$
w	weightage given to the cost estimated by regulator	0 to 1
R	DSO forecast cost/regulator's benchmark	–

Abbreviation	Descriptions	Equation/Constraint
SF	Sharing factor	$(R-R_{ref}) \bullet SF_{slope} + SF_{ref} + (E-AR) \bullet ROC$
$\mathbf{R_{ref}}$	R's reference point	–
$\mathbf{SF_{slope}}$	Slope of SF across R	< 1
$\mathbf{SF_{ref}}$	SF's reference value at R_{ref}	0 to 1
E	Actual expenditure	–
ROC	Constant rate of change of SF across E in relation to difference between the E and AR	$(SF_{ref}+R \bullet SF_{slope} - R_{ref} \bullet SF_{slope})/2 \bullet (AR-E_{limit})$ ROC < 1 produces SF which decreases with E ROC > 1 produces SF which increases with E
$\mathbf{E_{limit}}$	Actual expenditure used to calculate the limit of ROC. E_{lowest} to produce ROC > 1 while $E_{highest}$ to produce ROC < 1	–

Abbreviation	Descriptions	Equation/Constraint
AI	Additional income	$\alpha_1 R^2 + \alpha_2 R + \alpha_3$
$\boldsymbol{\alpha_1}$	Coefficient of second order term in AI	$(SF_{slope} \bullet (2w-1) + 2 \bullet ROC \bullet w(w-1))/2$
$\boldsymbol{\alpha_2}$	Coefficient of first order term in AI	$SF_{slope}(R_{ref} - 100w - R_{ref} \bullet w) + 200 \bullet ROC \bullet w(1-w) + SF_{ref}(w-1)$
$\boldsymbol{\alpha_3}$	Constant term in AI	$AI_{ref} - \alpha_1 R_{ref}^2 - \alpha_2 R_{ref}$
$\mathbf{AI_{ref}}$	AI's reference value at R_{ref}	–

Appendix J: Investment cost for rural area

Rural Investment Cost

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	7701	844277	4321354	6274897	7916041	10371777	12562698	9013246
CCTT	0	0	0	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0	0
SSEE	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0
ST	0	0	0	0	0	0	0	0	0	0

Rural preventive + corrective cost (annual)

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	12	1154	6282	9236	11511	14898	18081	13114
CCTT	0	0	0	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0	0
SSEE	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0
ST	0	0	0	0	0	0	0	0	0	0

Rural protection + regulator cost (NPV)

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	0	21282	131239	157842	219914	250064	283760	214594
MT	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0

Rural total cost (NPV)

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	7916	885853	4563047	6595143	8338355	10883799	13164373	9458423
CCTT	0	0	0	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0	0
SSEE	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0
ST	0	0	0	0	0	0	0	0	0	0

Rural PV Generation

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
peak demand P	2148	4297	6456	8633	10787	12947	15103	17219	19331	21477
peak generation P	8592	17187	25826	34531	43147	51788	60411	68875	77322	85908
peak demand Q	706	1412	2122	2837	3545	4255	4964	5660	6354	7059
peak generation Q	2824	5649	8488	11350	14182	17022	19856	22638	25414	28236

Appendix K: Investment cost for urban area

Urban Investment Cost

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	0	0	47554	174406	619244	1678536	2937326	6039069
CCTT	0	0	0	0	0	0	0	0	0	472820
MT	7517	0	0	0	0	0	0	0	1474	75361
SSEE	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0
ST	0	0	0	0	0	0	0	0	0	0

Urban preventive + corrective cost (annual)

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	0	0	63	261	864	2308	3979	8293
CCTT	0	0	0	0	0	0	0	0	0	10500
MT	36	0	0	0	0	0	0	0	18	391
SSEE	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0
ST	0	0	0	0	0	0	0	0	0	0

Urban protection + regulator cost (NPV)

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	0	0	0	3547	1774	3547	12415	65620
MT	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0

Urban total cost (NPV)

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
BT	0	0	0	0	48657	182551	636212	1722673	3019712	6250511
CCTT	0	0	0	0	0	0	0	0	0	657440
MT	8154	0	0	0	0	0	0	0	1786	82226
SSEE	0	0	0	0	0	0	0	0	0	0
AT	0	0	0	0	0	0	0	0	0	0
ST	0	0	0	0	0	0	0	0	0	0

Urban PV Generation

percentage of PV to consumers	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
peak demand P	10560	21112	31586	42103	52658	63260	73847	84418	95006	105562
peak generation P	42240	84446	126344	168413	210631	253040	295389	337673	380026	422247
peak demand Q	3471	6939	10382	13838	17308	20792	24272	27747	31227	34696
peak generation Q	13883	27755	41526	55353	69229	83168	97087	110985	124906	138783