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The choice of energy saving modes for an energy-intensive manufacturer considering non-energy benefits

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ABSTRACT

In practice, energy-intensive manufacturers have two main options when improving their energy efficiency: design and implement energy efficiency projects on their own (we call this self-saving) or enter into an energy performance contracting (EPC), which mainly includes shared savings and guaranteed savings. In this paper, we will discuss an energy-intensive manufacturer facing self-saving and shared savings options and how this manufacturer chooses the optimal energy saving mode when non-energy benefits are considered. We only consider "costs and profit" as non-energy benefits and formulate an optimization model of self-saving and a Stackelberg game model of shared savings. From our model analysis, when considering only energy savings, we find that the optimal unit savings has a monotonic impact on the optimal profit of the manufacturer. Our results indicate that: the manufacturer will prefer the second option to the first when the investment cost factor ratio of the energy service company (ESCO) to the manufacturer is small; otherwise, the manufacturer will prefer the first to the second. Furthermore, when considering non-energy benefits, we find that the results change in some cases.

1. Introduction

Improving energy efficiency is one of the most effective means by which energy-intensive manufacturers (hereafter abbreviated as manufacturers) can address the "three big mountains", i.e., the rapid rise in energy prices, increasingly stringent environmental policies, and growing consumer awareness of environmental protection. China intends to achieve its peak CO_2 emissions in approximately 2030 (U.S.-China Joint Announcement on Climate Change, 2014). To cope with Toxic Haze, more than 2100 industrial enterprises in China's capital of Beijing have ceased or limited their production of goods. For example, Xu Lejiang, the chairman of China's iron and steel association and the Baosteel group, believes that environmental and resource limitations have become an important reason for the current low-profit plight and that scientific and technological innovations should be used to address the high consumption and the high emissions of production processes. Kim and Worrell (2002a) benchmarked the energy efficiency of steel production to the best practice performance in five countries with over 50% world steel production, finding that potential carbon emission reductions due to energy-efficiency improvement varying from 15% (Japan) to 40% (China, India, and the USA). In the cement industry, benchmarking and other studies have demonstrated the technical potential for up to 40% improvement in energy efficiency (Kim and Worrell, 2002b).

In practice, manufacturers can design, construct and operate energy efficiency projects on their own to improve energy efficiency. This approach has some common characteristics: manufacturers mainly depend on their own strength, they provide project financing themselves, and they bear all the risks of projects but retain all the savings. For the sake of brevity, we will call this self-saving in this paper. For example, in 2005, Pfizer Fribourg, as one of the world's largest biopharmaceutical companies, began to improve its energy efficiency by self-saving. The company implemented an energy master plan, which includes geothermal heating and cooling, installation of wood-pellet boilers, and so on; this achieved good economic, environmental and social impacts (Aflaki and Kleindorfer, 2010). However, there are many disadvantages when manufacturers choose self-saving. For example, the energy efficiency equipment chosen by manufacturers might not be suitable for their energy efficiency projects, or the projects designed by manufacturers might not be reasonable due to lack of knowledge

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and experience during project design phases. Other risks are that energy efficiency equipment may age rapidly due to uninformed use or that actual energy savings may not always match expected energy savings during the phase of operating the projects. All the above factors may lead to the failure of project savings not making up for investment costs, which results in many potential energy efficiency projects not being implemented.

To solve these problems, manufacturers can outsource energy services to energy service companies (ESCOs). Larsen et al. (2012) defined an energy service company as a company that provides energy-efficiency-related and other value-added services and for which performance contracting is a core part of its energy-efficiency services business. In a performance contract, the ESCO guarantees energy and/or dollar savings for the project and the ESCO's compensation is therefore linked in some way to the performance of the project. Typically, the main form of energy services provided by ESCOs is energy performance contracting (EPC). According to a survey of 65 foundries in France, Italy, Germany and seven other countries, approximately 25% of responding enterprises prefer EPC to self-saving (Thollander et al., 2013). Another example is that of China's Qinling Cement Co., Ltd. As one of China's key cement enterprises, Qinling chose EPC in 2008 (Song and Geng, 2011). EPC, which emerged in North America in the 1970s after the first oil crisis, is a new market mechanism in which a manufacturer outsources energy services to an ESCO, which pays for the investment costs of energy efficiency projects by reducing energy costs and provides the manufacturer with comprehensive energy services, including energy audits, investments in equipment, equipment selection, and all aspects of operation and maintenance. The use of EPC in China began with the Energy Performance Contracting Project, a collaboration between China's government and the World Bank in 1998, and since then EPC has been increasingly welcomed by governments and enterprises. According to "The Development Report of China's ESCOs" in 'the 11th Five-Year Plan', there will be 2500 ESCOs by 2015. There are two general types of performance contracts used in the ESCO industry: shared savings and guaranteed savings (Larsen et al., 2012). In a shared savings contract, the ESCO provides the financing, and the client assumes no financial obligations other than paying a given share of the materialized savings to the ESCO over a prescribed period of time (we call this an agreed contract term). After the agreed contract term, the customer retains all the savings until the end. Alternatively, in a guaranteed savings contract, projects are often financed by a third party financial entity; the customer repays the loan to this creditor, and the ESCO guarantees a level of savings sufficient to cover the annual debt obligation, thus limiting the customer's performance risk. The shared savings approach is more suitable in developing countries, where energy efficiency projects lack a reliable and commercially viable means of financing, and energy-intensive customers always pursue short-term economic benefits and are reluctant to invest in energy efficiency projects. In China, shared savings is widely used, as government support for this approach is an important impetus in addition to the above-mentioned reasons. For example, both the tax cut policy released in 2010 and the financial incentives policy released in 2011 clearly require the use of shared savings; there are no similar policies to support guaranteed savings in China (Qian and Guo, 2014). Therefore, we only consider shared savings in this paper.

Comparing self-saving with shared savings, an ESCO always has a cost advantage with regard to the specialty of improving energy efficiency; it has more experience, more advanced technologies, and enjoys volume discounts when buying equipment. However, the ESCO and the manufacturer have to share the savings, which we call the cost difference in this paper. The cost difference is an important factor encouraging the manufacturer to choose the optimal energy savings mode. Moreover, the manufacturer can not only achieve energy savings from energy efficiency projects but can also obtain non-energy benefits, such as decreased CO_2 emissions, reduced labour and maintenance costs, improved productivity, improved product quality, improved working environment and so on (Larsen et al., 2012; Pye and McKane, 2000; Worrell et al., 2003). Pye and McKane (2000), investigating many energy efficiency projects, find that non-energy benefits always exceed energy savings. Worrell et al. (2003) show that considering non-energy benefits can significantly decrease energy saving costs; in a study of more than 70 industrial cases, they compare energy-saving costs, taking non-energy benefits into account, with energy-saving costs without consideration of non-energy benefits. However, because non-energy benefits under the two energy saving modes are different (we call this the non-energy benefits difference), this is another important factor in whether a manufacturer chooses the optimal energy saving mode. To focus on the cost and non-energy benefits differences, we do not consider other factors influencing the optimal choice of energy saving modes, such as financing, risk-sharing and so on. Based on the above analysis, we focus on the cost and non-energy benefits differences and investigate the problem of choosing between energy saving modes for a perfect monopoly manufacturer deciding between self-saving and shared savings when non-energy benefits are considered. We try to answer two questions: (1) given an energy saving mode, how do the manufacturer and the ESCO make their optimal decisions? (2) what is the optimal choice between energy saving modes for the manufacturer?

Because there are different non-energy benefits and some non-energy benefits, such as quality and waste flows and so on, are difficult to calculate as "costs and profit", we only consider "costs and profit" as non-energy benefits. To answer our research questions, we establish an optimization model of self-saving and a Stackelberg game model of shared savings. We use a relatively small investment cost factor for the ESCO to characterize the cost difference, and we use the different rates of returns of non-energy benefits under the two energy saving modes to characterize the non-energy benefits difference. When the manufacturer chooses self-saving, the entire process of improving energy efficiency can be generally divided into the design phase, the construction phase and the operation phase. During the design phase, the manufacturer designs different energy efficiency projects, which have different savings and investment costs, and chooses suitable projects by balancing project savings and investment costs. Assuming the energy price is fixed, the project savings is often proportional to the unit savings. Therefore, when the manufacturer chooses self-saving, the unit savings and the investment costs are the two decision variables of the manufacturer. Because the relation between the unit savings and the investment costs is a marginal increase, we regard the unit savings as the only decision variable of the manufacturer and develop the optimization model of self-saving (see Section 3.1 for details). When the manufacturer chooses shared savings, the entire process of improving energy efficiency can be generally divided into the audit phase, the design phase, the contract negotiation phase, the construction phase and the operation phase. During the contract negotiation phase, the project savings (similar to self-saving, we use unit savings to characterize project savings), the fraction of unit savings and the agreed contract term are the three decision variables between the manufacturer and the ESCO. These three variables are also recommended for use in "China's EPC technical specifications". The relation between the fraction of unit savings and the agreed contract term is an inverse relationship, i.e., if the ESCO realizes a larger fraction of unit savings, then it will obtain a shorter agreed contract term and vice versa. Therefore, we regard only the unit savings and the fraction of unit savings as the decision variables. Because the energy efficiency projects are designed by the ESCO, it is reasonable that the ESCO determines the unit savings, then the manufacturer has to determines the fraction of unit savings to negotiate with the ESCO. The Stackelberg game model has been widely used in other fields. However, fewer researchers introduce this game model into energy-efficiency management (see Section 2). Besides, during the decision process, on the one hand the manufacturer and the ESCO always have different leaderships; on the other hand, they always pursue their own interests and the energy-saving supply chain with the manufacturer and the ESCO could be inefficient for their decentralized decisions, i.e., double marginalization effect. We can simulate these characteristics by formulating the Stackelberg model, which can help us analyze how they make their optimal decisions and how their optimal decisions affect the optimal choice between energy saving modes for the manufacturer. Based on the above considerations, we establish a Stackelberg game model between the manufacturer and the ESCO (see Section 3.2 for details). Through model analysis, we derive Table 1 and Propositions 1–7 to answer our research questions and develop an analytical framework for manufacturers choosing their optimal energy-saving modes (see Section 6.2).

The remaining contents are organized as follows: Section 2 reviews the relative literature. We describe the research problem and formulate the mathematical models under two energy saving modes in Section 3. In Section 4, we analyze the models. Numerical examples are provided in Section 5. Section 6 discusses two model assumptions and develops an implication framework of choosing the optimal energy saving mode. Finally, we conclude the paper and formulate the future research in Section 7. Some supplemental materials and all the important proofs are placed in Appendix A and Appendix B, respectively.

2. Literature review

Our paper is closely related to the choice between self-saving and EPC. However, the related literature is extremely scarce and previous studies have focused on the ESCO industry market, the ESCO development and the contract terms of EPC. Regarding the ESCO industry market: Vine (2005) examines the current level of ESCO activity in 38 countries outside of the US; Bertoldi et al. (2006) and Marino et al. (2011) review and analyze the development and the current status of ESCO industries in the EU; Goldman et al. (2005) review the US ESCO industry market trends; Larsen et al. (2012) build on Goldman et al. (2005) and review the evolution of the U.S. ESCO industry; Yuan et al. (2016) examine the status and future of EPC in China. Regarding the ESCO development: Lee et al. (2003) introduce experience from Korean ESCO business and show that financing is not the most crucial barrier; Zhang et al. (2014) study the "Turning green into gold" problem and develop a framework for EPC in China's real estate industry; Larsen et al. (2012) think that non-energy benefits between the ESCOs and their customers should be incorporated into benefit-cost (i.e., contractual) frameworks; Mills et al. (2006) classify the risks associated with energy efficiency projects into five aspects, namely economic, contextual, technology, operation, and measurement and verification (M&V) risks, and suggest that firms should transfer risks via energy-saving insurance (Mills, 2003); Painuly et al. (2003) promote energy efficiency financing and ESCOs in developing countries. However, most of the above two types of studies analyze the ESCOs from a macro perspective and the analyses on the decisions of the ESCOs and the customers are not enough. Unlike them, we focus on the manufacturers' decisions. Regarding the contract terms of EPC: Qian and Guo (2014) develop a revenue-sharing bargaining model to design the energy saving and revenue sharing strategy of ESCOs; Deng et al. (2015a) develop an approach for the ESCOs to make optimal investment decisions; Deng et al. (2015b) propose a methodology to design strategy of cost saving guarantee in EPC; Lee et al. (2015) determine a profit distribution in guaranteed savings based on the collar option model. All the above studies involve the contract terms of EPC, but they focus on the ESCOs. Unlike them, our paper focuses on manufacturers. Regarding the choice between self-saving and EPC, few researchers devote to discussing the conditions of outsourcing energy services because EPC belongs to a form of outsourcing. Fawkes (2007) shows that a manufacturer in three situations, which includes reducing more energy costs or carbon emissions, considering the potential points of reducing costs or needing to update equipment when capitals are limited, may outsource energy services. Assuming that energy costs consist of production costs and transaction costs, Sorrell (2007) believes that three main outsourcing conditions must exist—and one of them is that reduced production costs are larger than increased transaction costs in outsourcing process. Vine (2005) shows that in addition to these key barriers for the end user, there are also barriers cited that are more policy-related. In a word, most of the above studies devote to comparing energy saving modes by qualitative or empirical methods. To the best of our knowledge, the related quantitative analysis is scarce and few

Table 1
The optimal decisions of the ESCO and the manufacturer and the optimal profits of the manufacturer under the two energy saving modes ($f_0>0$, $f_i=0$ or 1).

			Self-savings (b)	Shared savings (s)
Considering only energy savings ($f_0=0$)		$r^*_{i,no}$	$p_eDr_0^2/k$	$p_eDr_0^2/(2\alpha k)$
		φ^*_{no}	–	1/2
		$\prod_{mi}(r^*_{i,no})$	$A+(p_eDr_0)^2/(2k)$	$A+(p_er_0D)^2/(4\alpha k)$
		Feasible conditions	$k>p_eDr_0$	$\alpha k>(1-\varphi_{no})p_eDr_0$
Considering non-energy benefits ($f_0>0$)	$f_i=0$	$r^*_{i,sma}$	$p_eDr_0^2/k$	$p_eDr_0^2/(2\alpha k)$
		φ^*_{sma}	–	1/2
		$\prod_{mi}(r^*_{i,sma})$	$A+(p_eDr_0)^2/(2k)+f_0$	$A+(p_er_0D)^2/(4\alpha k)+f_0$
		Feasible conditions	$k>p_eDr_0$	$\alpha k>(1-\varphi_{sma})p_eDr_0$
	$f_i=1$	$r^*_{i,big}$	$(p_eDr_0+f_0)r_0/k$	$(p_eDr_0+f_0)r_0/(2\alpha k)$
		φ^*_{big}	–	$1/2-f_0/(2p_eDr_0)$
		$\prod_{mi}(r^*_{i,big})$	$A+(p_eDr_0+f_0)^2/(2k)$	$A+(p_eDr_0+f_0)^2/(4\alpha k)$
		Feasible conditions	$k>p_eDr_0+f_0$	$\alpha k>(1-\varphi_{big})p_eDr_0$, $p_eDr_0\geq f_0$

Notes: $A=(p-c-r_0p_e)D$; $r^*_{i,j}$ means the optimal unit savings; φ^*_j means the optimal fraction of unit savings; $\prod_{mi}(r^*_{i,j})$ represents the optimal profit of the manufacturer; $i=b,s$ represent self-saving and shared savings, respectively; $j=no,sma$, big represent that only energy savings are considered ($f_0=0$), the rates of non-energy benefits returns are small when non-energy benefits are considered ($f_0>0,f_i=0$), the rates of non-energy benefits returns are big when non-energy benefits are considered ($f_0>0,f_i=1$), respectively.

researchers consider the choice of energy saving modes when non-energy benefits are considered. In this paper, we not only study the choice between energy saving modes by mathematical models but also consider non-energy benefits.

3. Problem description

A manufacturer (she, denoted by subscript m) in a perfect monopoly market that needs to save energy makes two-stage decisions. In the first stage, facing self-saving (denoted by subscript b) and shared savings (denoted by subscript s), assuming that the two types of energy saving systems both have one-unit life cycles, the manufacturer determines an optimal choice by comparing her optimal profits under the two energy saving modes. In the second stage, we assume that the manufacturer produces a product and the demand D is not random. To avoid trivial discussion, we assume that the marginal profit before improving energy efficiency is positive, i.e., $p>c+r_0p_e$, where p represents the retail price of the product, c represents the unit production cost, p_e represents the energy price and r_0 represents the unit's initial energy level (tce/unit). When considering self-saving, the manufacturer considers the savings and the investment cost of energy efficiency projects and then determines the optimal unit savings to maximize her profit. When considering shared savings, assuming that the manufacturer and the ESCO (he, denoted by the subscript e) are both risk-neutral, their reservation utilities are zero and information is completely symmetrical, they have a Stackelberg game. The manufacturer, as a leader with relatively strong strength (e.g., iron and steel companies, cement companies and so on) determines the optimal fraction of unit savings and the ESCO, as a follower, determines the optimal unit savings. Both of them maximize private profits, and we report the details in Section 3.1 and Section 3.2. In the following, we describe the non-energy benefits and the investment costs.

(1) The non-energy benefits

We assume that the better the energy saving effects for the manufacturer, the more non-energy benefits she receives, and an energy saving rate is often used to measure the effects of energy saving technology in practice. Then, similar to Xiao and Gaimon (2013), we assume that the non-energy benefits are $f_0(r_i/r_0)^{f_i}$, where r_i $(0\le r_i<r_0)$ represents the unit savings; r_i/r_0 represents the energy saving rate; $r_i<r_0$ means that the unit savings are not larger than the unit's initial energy level; $f_0\ge 0$ represents a scaling factor of energy saving effects (which reflects how much the manufacturer can gain from the non-energy benefits); $f_0=0$ means that the manufacturer does not gain any non-energy benefits (e.g., only energy savings are considered, or the non-energy benefits are so small that they are omitted) and we denote this case by subscript *no*; $f_i\in[0,1]$ represents the rate of non-energy benefits returns; $f_i=0$ means that the rate of non-energy benefits returns is small (denoted by subscript *sma*); $f_i\in(0,1)$ reflects that the rate of non-energy benefits returns is decreasing (we call this the general case in this paper); $f_i=1$ means that the rate of non-energy benefits returns is large (denoted by subscript *big*), such as when many energy efficiency projects are simultaneously implemented by a manufacturer or an energy efficiency project is simultaneously implemented in a group company; $i=b,s$ represent self-saving and shared savings, respectively. Our assumption is slightly different from that of papers related to manufacturing outsourcing (Gray et al., 2009; Xiao and Gaimon, 2013). A common assumption in the relevant literature is that the manufacturer will accumulate production experience through in-house production and will gain volume-based knowledge; otherwise, it will lose the chance of volume-based learning if it chooses manufacturing outsourcing. Our research background is different. Unlike previous studies, we assume that whatever the manufacturer chooses as her energy saving mode, because those energy efficiency projects are implemented in-house, she always has the opportunity to learn. Although the manufacturer may accumulate more experience when choosing self-saving, she may gain more advanced energy saving technologies or equipment when choosing shared savings. So, we do not assume the size of the relationship between f_b and f_s.

(2) The investment cost

As mentioned above, because the energy saving rate is often used to reflect the effects of certain energy saving technologies, we assume that the investment cost is a quadratic function of the energy saving rate r_i/r_0. Given self-saving, the investment cost is $k(r_b/r_0)^2/2(k>0)$, where k represents the investment cost factor and reflects the relationship between the investment cost and the energy saving rate. The larger the factor is, the more sensitive the relationship is. The quadratic function not only describes the phenomenon of increasing marginal cost but also reflects the characteristic that the investment cost of the unit's initial energy level is decreasing. The higher the unit's initial energy level is, and the more potential energy efficiency projects the manufacturer has, the more she can improve energy efficiency in no-cost or low-cost ways. For example, approximately 25% of savings at Owens Corning are generated in low-cost or no-cost ways, such as more efficient management, storage temperature control and so on. Because the ESCO is more professional than the manufacturer, let $k_s=\alpha k(0<\alpha\le 1)$, where α represents the investment cost factor ratio of the ESCO to the manufacturer, i.e., the investment cost under shared savings is $\alpha k(r_s/r_0)^2/2$. To satisfy $0\le r_i<r_0$, i.e., internal solution r_i exists, we assume k, αk are large enough, i.e., this means that the investment cost is not too inexpensive, which is consistent with many economic literature (Gilbert and Cvsa, 2003; Ofek et al., 2011). The operating cost of an energy saving system mainly includes energy costs (included in energy costs after improving energy efficiency) and ignores other operating costs, such as labour costs, maintenance costs and so on.

First, given an energy saving mode, we begin to formulate mathematical models of self-saving and shared savings.

3.1. Self-saving scenario

Under the self-saving scenario, the manufacturer needs to audit energy costs from production costs to measure the savings provided by energy efficiency projects. For example, the energy management process at Siemens consists of an identification phase, an evaluation phase and an implementation phase. In the identification phase, an energy audit assists in determining potential energy saving points. Moreover, this method is typically recognized in the literature (Xiao and Gaimon, 2013). Therefore, we assume that the unit production cost consists of the unit production cost except for the unit energy cost c (we call this unit non-energy production cost) and the unit energy cost r_0p_e. The manufacturer determines the unit savings to maximize her profit. The optimization model of self-saving is as follows:

$$\text{Max} \prod\nolimits_{mb}(r_b) = [p-c-(r_0-r_b)p_e]D + f_0(r_b/r_0)^{f_b} - k(r_b/r_0)^2\Big/2 \tag{1}$$

$$\text{s.t. } 0 \le r_b < r_0. \tag{2}$$

The first term in (1) is the sales revenue, the second term in (1) is the non-energy benefits and the third term in (1) represents the investment cost. Constraint (2) means that the unit savings are less than the unit's initial energy level.

3.2. Shared savings scenario

Under the shared savings scenario, the manufacturer first determines the fraction of unit savings φ ($0 \leq \varphi < 1$) to maximize her profit. Then, the ESCO determines the unit savings r_s to maximize his profit. We assume that an agreed contract term is T_s ($0 \leq T_s \leq 1$). During the agreed contract term, the manufacturer and the ESCO share the savings according to the fraction of unit savings, so the unit production cost is $c+(r_0-\varphi r_s)p_e$. When the agreed contract term is over, the manufacturer holds all the savings until the end of the system's life cycle. To simplify the problem, we assume $T_s=1$ (we can easily prove this assumption has no impact on our results of our paper). In addition, we assume that the ESCO cannot obtain the non-energy benefits (such as decreased labour cost, improved product quality, more comfortable work environment and so on) because it is difficult to quantify them.

The manufacturer first determines the fraction of unit savings to maximize her profit. The model is as follows:

$$\text{Max } \prod_{ms}(\varphi) = [p - (c + (r_0 - \varphi r_s)p_e]D + f_0(r_s/r_0)^{f_s} \tag{3}$$

$$\text{s.t. } \prod_{es}(r_s) \geq 0, \;\; 0 \leq \varphi < 1. \tag{4}$$

Objective function (3) represents the profit of the manufacturer which is equal to the sum of the product between the marginal profit and the market demand and the non-energy benefits, where the difference from objective function (1) is that the manufacturer using shared savings does not include the investment cost. Constraints (4) represent the participation constraint of the ESCO and the range of the fraction of unit savings, respectively.

Then the ESCO determines the unit savings to maximize his profit. The model is as follows:

$$\text{Max } \prod_{es}(r_s) = (1-\varphi)r_s p_e D - \alpha k (r_s/r_0)^2 \Big/ 2 \tag{5}$$

$$\text{s.t. } 0 \leq r_s < r_0. \tag{6}$$

Objective function (5) represents the profit of the ESCO which is equal to the share savings from energy efficiency projects minus the investment cost. Constraint (6) is similar to the constraint (2).

4. Model analysis

In the following, we solve the above models by backward induction.

4.1. The optimal decisions of the ESCO and the manufacturer given an energy saving mode

First, we solve the model of self-saving and derive that the optimal unit savings r_b^* satisfies the condition:

$$p_e D - k r_b^* \Big/ r_0^2 + f_0 f_b r_0^{-f_b} r_b^{*(f_b-1)} = 0. \tag{7}$$

Second, we solve the Stackelberg game model of shared savings and derive that the optimal unit savings r_s^* and the optimal fraction of unit savings φ^* satisfy the conditions:

$$(1-2\varphi^*)(p_e r_0 D)^2 \Big/ \alpha k - f_0 f_s r_0^{-f_s} \left(p_e D r_0^2 \Big/ \alpha k\right)^{f_s} (1-\varphi^*)^{(f_s-1)} = 0, \tag{8}$$

$$r_s^* = (1-\varphi^*) p_e D r_0^2 \Big/ (\alpha k). \tag{9}$$

Because expressions (7)–(9) are complicated, the management insights are difficult to derive. To simplify the analysis, we consider three special cases, i.e., only energy savings are considered ($f_0=0$), the rates of non-energy benefits returns under self-saving or shared savings are small when non-energy benefits are considered ($f_0>0$, $f_i=0$), the rates of non-energy benefits returns under self-saving or shared savings are large ($f_0>0$, $f_i=1$) when non-energy benefits are considered. We derive the optimal decisions of the ESCO and the manufacturer and the optimal profits of the manufacturer under the two energy saving modes, as shown in Table 1.

From Table 1, we indicate that when the energy price, the demand, the unit's initial energy level and the scaling factor of energy saving effects increases or the investment cost factor decreases the manufacturer would like to raise the optimal unit savings to gain a more optimal profit. Interestingly, the optimal fraction of unit savings when only energy savings are considered is 1/2, which is consistent with the finding that a 50–50 split is the optimal solution in a "sharecropping" problem (Hurwicz and Shapiro, 1978). However, this may not be correct under non-energy benefits cases.

We regard considering only energy savings as a benchmark. From Table 1, we have Proposition 1 and Proposition 2.

Proposition 1. Under self-saving scenario, we have,

$$(1)\;\; r^*_{b,no} = r^*_{b,sma} < r^*_{b,big}; \quad (2)\;\; \prod_{mb}\left(r^*_{b,no}\right) < \prod_{mb}\left(r^*_{b,sma}\right) < \prod_{mb}\left(r^*_{b,big}\right).$$

Proposition 1 shows that when the manufacturer considers non-energy benefits, compared with considering only energy savings, she can obtain more savings by choosing a bigger optimal unit savings. We theoretically demonstrate the empirical result (Pye and McKane, 2000; Worrell et al., 2003), i.e., that considering non-energy benefits will increase the manufacturer's motivation to improve energy efficiency.

Proposition 2. Under shared savings scenario, we have,

$$(1)\;\; r^*_{s,no} = r^*_{s,sma} < r^*_{s,big}, \quad (2)\;\; \varphi^*_{no} = \varphi^*_{sma} > \varphi^*_{big};$$

$$(3)\;\; \prod_{ms}(\varphi^*_{no}) < \prod_{ms}(\varphi^*_{sma}) < \prod_{ms}\left(\varphi^*_{big}\right); \quad (4)\;\; \prod_{es}\left(r^*_{s,no}\right) = \prod_{es}\left(r^*_{s,sma}\right) < \prod_{es}\left(r^*_{s,big}\right).$$

Proposition 2 shows that when the manufacturer considers non-energy benefits, compared with considering only energy savings, the manufacturer gives the ESCO an equal or a larger optimal fraction of unit savings and the ESCO is motivated to produce a bigger optimal unit savings. Both companies gain more savings. Proposition 2 indicates that considering non-energy benefits increases the motivations of the two companies to improve energy efficiency and creates a win-win situation.

4.2. The optimal choice between energy saving modes for the manufacturer

We go back to the first stage and the manufacturer determines the optimal choice between energy saving modes. As mentioned above, we also regard considering only energy savings as the benchmark. According to whether non-energy benefits are considered or not, two cases $f_0=0$, $f_0>0$ will be discussed.

4.2.1. Considering only energy savings ($f_0=0$) case

This case means that the energy efficiency projects cannot bring the manufacturer non-energy benefits. For simplicity, let $t=p_e r_0 D$, which means the total energy cost to the manufacturer. From Table 1, we derive Proposition 3.

Proposition 3. Given self-saving and shared savings, assuming $f_0=0$, then,

(1) if $t/(2k)<\alpha<1/2$, then $r^*_{s,no}>r^*_{b,no}$, $\prod_{ms}(\varphi^*_{no})>\prod_{mb}\left(r^*_{b,no}\right)$;

(2) if $\alpha=1/2$, then $r^*_{s,no}=r^*_{b,no}$, $\prod_{ms}(\varphi^*_{no})=\prod_{mb}\left(r^*_{b,no}\right)$;

(3) if $1/2<\alpha\le 1$, then $r^*_{s,no}<r^*_{b,no}$, $\prod_{ms}(\varphi^*_{no})<\prod_{mb}\left(r^*_{b,no}\right)$.

Proposition 3 contrasts the optimal unit savings and the optimal profits of the manufacturer under two energy saving modes. The optimal choice between energy saving modes is shown as Fig. 1.

As shown in Fig. 1, if the investment cost factor ratio of the ESCO to the manufacturer is small, i.e., $t/(2k)<\alpha<1/2$, the manufacturer prefers shared savings. Because the ESCO has a smaller investment cost factor, i.e., αk, then he raises the optimal unit savings and increases the project savings. Although the project savings must be shared with the ESCO, the manufacturer can still obtain more profit. Otherwise, i.e., $1/2<\alpha<1$, the manufacturer prefers self-saving because the cost advantage of the ESCO is not obvious. Proposition 3 demonstrates the intuition that the investment cost factor ratio of the ESCO to the manufacturer is a key factor which has a strong impact on the optimal choice between energy saving modes. Moreover, we find that the threshold value of changing the energy saving mode $\alpha=1/2$ is a constant, which is independent of the total energy cost and the investment cost factor. Finally, we indicate that the optimal unit savings has a monotonic impact on the manufacturer's optimal profit. That is, the bigger the optimal unit savings is, the more optimal profit the manufacturer can obtain and vice versa.

4.2.2. Considering non-energy benefits ($f_0>0$) case

Considering the complicated expressions (7)–(9), to derive some management insights we first consider the extreme cases that the rates of non-energy benefits returns are extreme values, i.e., $f_i=0$ or 1. Next, we discuss the general case ($0<f_b,f_s<1$). More specifically, according to the size of the relationship between the rates of non-energy benefits returns under two energy saving modes, we discuss four cases, i.e., $f_b>f_s(f_b=1,f_s=0)$, $f_b=f_s(0$ or $1)$, $f_b<f_s(f_b=0,f_s=1)$ and $0<f_b,f_s<1$.

(1) $f_b>f_s(f_b=1,f_s=0)$case

The case means that the rate of non-energy benefits returns under self-saving is bigger than the rate of non-energy benefits returns under shared savings. We easily derive Proposition 4 and Proposition A.1 (see Appendix A).

Proposition 4. Given self-saving and shared savings, assuming $f_0>0$ and $f_b>f_s$ $(f_b=1,f_s=0)$, the optimal choice between energy saving modes is as follows:

(a) if $t\le\sqrt{2}f_0$, when $k>t+f_0$ and $t/(2k)<\alpha\le 1$, $\prod_{ms}(\varphi^*_{sma})>\prod_{mb}(r^*_{b,big})$; ;
(b) if $t>\sqrt{2}f_0$,
  (i) When $k>[2(t+f_0)^2-t^2]/(4f_0)$ and $t/(2k)<\alpha\le 1$, $\prod_{ms}(\varphi^*_{sma})>\prod_{mb}(r^*_{b,big})$;
  (ii) When $t+f_0<k\le[2(t+f_0)^2-t^2]/(4f_0)$,
    ① if $t/(2k)<\alpha<t^2/[2(t+f_0)^2-4kf_0]$, $\prod_{ms}(\varphi^*_{sma})>\prod_{mb}(r^*_{b,big})$;
    ② if $\alpha=t^2/[2(t+f_0)^2-4kf_0]$, $\prod_{ms}(\varphi^*_{sma})=\prod_{mb}(r^*_{b,big})$;
    ③ if $t^2/[2(t+f_0)^2-4kf_0]<\alpha\le 1$, $\prod_{ms}(\varphi^*_{sma})<\prod_{mb}(r^*_{b,big})$.

Proposition 4 contrasts the optimal profits of the manufacturer under the two energy saving modes, where the non-energy benefits are considered and the rate of non-energy benefits returns under self-saving is bigger than the rate of non-energy benefits returns under shared savings. Proposition 4(a) shows that when the total energy cost to the manufacturer is less than a threshold value ($\sqrt{2}f_0$), the dominant factor in the optimal profit of the manufacturer is the non-energy benefits. Because the relatively higher rate of non-energy benefits returns under self-saving leads to fewer non-energy benefits under self-savings, it is always the best choice that the manufacturer chooses shared savings. After the total energy cost to the manufacturer reaches the threshold value ($\sqrt{2}f_0$), as shown in Proposition 4(b), the non-energy benefits and the energy saving direct profit, which is equal to energy savings minus the investment cost (see expressions (1) or (3)), become the dominant factors in the optimal profit of the manufacturer. When the investment cost factor of the manufacturer is relatively large, the manufacturer can still utilize the cost advantage of the ESCO and gains more energy saving direct profit by choosing shared savings. When the investment cost factor of the manufacturer is a middle value, the impact of the cost advantage on the energy saving direct profit depends on the investment cost factor ratio of the ESCO to the manufacturer. If the investment cost factor ratio of the ESCO to the manufacturer is small, the cost advantage of choosing shared savings is still relatively big, and the manufacturer prefers shared savings. Otherwise, the manufacturer instead prefers self-saving for the unobvious cost advantage. Proposition 4b(ii) is shown in Fig. 2.

Comparing Fig. 1 with Fig. 2, we find that there are three changes in the optimal choice between energy saving modes for the manufacturer. First, the optimal choice between energy saving modes not only depends on the investment cost factor ratio of the

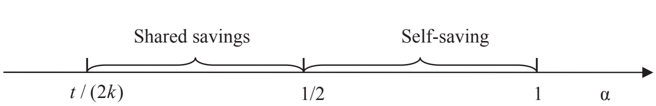


Fig. 1. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer ($f_0=0$).

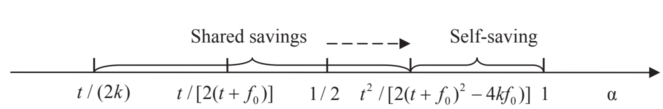


Fig. 2. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer ($t>\sqrt{2}f_0$, $t+f_0<k\le[2(t+f_0)^2-t^2]/(4f_0)$).

ESCO to the manufacturer but also depends on the total energy cost to the manufacturer, the investment cost factor of the manufacturer and the scaling factor of energy saving effects. Second, the relatively small non-energy benefits under self-saving narrow the range in which self-saving is chosen (shown by dashed arrow in Fig. 2.). For example, the threshold value moves from 1/2 to $[2(t+f_0)^2-t^2]/(4f_0)$ ($[2(t+f_0)^2-t^2]/(4f_0)>1/2$). Third, the impact of the optimal unit savings on the optimal profit of the manufacturer is not monotonic. When the investment cost factor ratio of the ESCO to the manufacturer is a middle value, the optimal unit savings under self-saving are bigger than the optimal unit savings under shared savings (as shown in Proposition A.1, $r^*_{s,sma}<r^*_{b,big}$), but the optimal profit of the manufacturer under self-saving instead is smaller than the optimal profit under shared savings (for $(t+f_0)/(2t)<\alpha<t^2/[2(t+f_0)^2-(4kf_0)]$, we know this easily), which is caused by the relatively small non-energy benefits under self-saving.

(2) $f_b=f_s(0 \text{ or } 1)$case

This case means that the rates of non-energy benefits returns are equal when choosing different energy saving modes, i.e., $f_b=f_s$ (0 or 1). We easily derive Proposition 5.

Proposition 5. Given self-saving and shared savings, assuming $f_0>0$ and $f_b=f_s$ (0 or 1), compared with considering only energy savings, the optimal choice between energy saving modes for the manufacturer is not changed.

Proposition 5 shows that when the rates of non-energy benefits returns under the two energy saving modes are equal, considering non-energy benefits would not change the optimal choice between energy saving modes for the manufacturer. The reason is that the equal rates of non-energy benefits returns make the same contribution to the optimal profits of the manufacturer.

(3) $f_b<f_s$ ($f_b=0, f_s=1$)case

This case means that the rate of non-energy benefits returns under self-saving is smaller than the rate of non-energy benefits returns under shared savings. We easily derive Proposition 6 and Proposition A.2 (see Appendix A).

Proposition 6. Given self-saving and shared savings, assuming $f_0>0$ and $f_b<f_s$ ($f_b=0$,$f_s=1$), the optimal choice between energy saving modes for the manufacturer is as follows:

(a) if $t=f_0$, when $(t+f_0)/(2k)<\alpha\le 1$, $\prod_{ms}(\varphi^*_{big})<\prod_{mb}(r^*_{b,sma})$;
(b) if $t>f_0$,
  (i) When $t<k\le t^2/(t-f_0)$ and $(t+f_0)/(2k)<\alpha\le 1$, $\prod_{ms}(\varphi^*_{big})<\prod_{mb}(r^*_{b,sma})$;
  (ii) When $k>t^2/(t-f_0)$,
    ① if $(t+f_0)/(2k)<\alpha<(t+f_0)^2/[2(t^2+2kf_0)]$, $\prod_{ms}(\varphi^*_{big})>\prod_{mb}(r^*_{b,sma})$;
    ② if $\alpha=(t+f_0)^2/[2(t^2+2kf_0)]$, $\prod_{ms}(\varphi^*_{big})=\prod_{mb}(r^*_{b,sma})$;
    ③ if $(t+f_0)^2/[2(t^2+2kf_0)]<\alpha\le 1$, $\prod_{ms}(\varphi^*_{big})<\prod_{mb}(r^*_{b,sma})$.

Proposition 6 also contrasts the optimal profits of the manufacturer under the two energy saving modes, where non-energy benefits are considered and the rate of non-energy benefits returns under self-saving is less than the rate of non-energy benefits returns under shared savings. Proposition 6(a) shows that when the total energy cost to the manufacturer is equal to the scaling factor of energy saving effects f_0, similar to Proposition 4(a), the dominant factor in the optimal profit of the manufacturer is the non-energy benefits. Because the relatively lower rate of non-energy returns under self-saving leads to more non-energy benefits, it is always the best choice that the manufacturer uses self-saving. After the total energy cost to the manufacturer reaches the threshold value f_0, as shown in Proposition 6(b), similar to Proposition 4(b), the dominant factors in the optimal profit of the manufacturer are the non-energy benefits and the energy saving direct profit (see Proposition 4 for explanation). When the investment cost factor is relatively small, it is always the best choice that the manufacturer uses self-saving. When the investment cost factor of the manufacturer is a middle value, if the investment cost factor ratio of the ESCO to the manufacturer is small, the manufacturer prefers shared savings. Otherwise, the manufacturer instead prefers self-saving. The reasons are similar to Proposition 4. Proposition 6 b(ii) is shown in Fig. 3.

Comparing Fig. 1 with Fig. 3 and from Proposition A.2, as shown in Proposition 4, we find that there are three changes in the optimal choice between energy saving modes for the manufacturer. Unlike Proposition 4, the difference is that the range in which self-saving is chosen is expanded. For example, the threshold value of changing energy saving mode moves from 1/2 to $(t+f_0)^2/[2(t^2+2kf_0)]$ and we can explain this as Proposition 4.

(4) The general case ($f_b\ne f_s\in(0,1)$)

In the above three cases, we analyze the cases in which the rates of non-energy benefits returns are extreme values. In the following, we discuss the general case, i.e., $f_b\ne f_s\in(0,1)$. From expressions (7)–(9), we insert r^*_b,r^*_s and φ^* into expressions (1) and (3) and directly have Proposition 7.

Proposition 7. Given self-saving and shared savings,

(1) if $\prod_{ms}(\varphi^*)>\prod_{mb}(r^*_b)$, the manufacturer prefers shared savings;
(2) if $\prod_{ms}(\varphi^*)=\prod_{mb}(r^*_b)$, the manufacturer prefers self-saving or shared savings;
(3) if $\prod_{ms}(\varphi^*)<\prod_{mb}(r^*_b)$, the manufacturer prefers self-saving.

Proposition 7 gives the conditions of the optimal choice between energy saving modes for the manufacturer and we further discuss this case. According to the analysis of extreme cases, we know that when the rates of non-energy benefits returns under the two energy saving modes are equal, as the non-energy benefits make the same contribution to the optimal profits of the manufacturer, the optimal profit of the manufacturer are only decided by the investment cost factor ratio of the ESCO to the manufacturer. Then, the main results are similar to the $f_b=f_s=0$ or 1 case. When the rates of non-energy benefits returns under the two energy saving modes are not equal, according to the analysis of extreme cases, we know the non-energy benefits and the energy saving direct profit (see Proposition 4 for explanation) may have an important impact on the optimal profits of the manufacturer. If the total energy cost to the manufacturer is small, only the non-energy benefits have an important impact on the optimal profits of the manufacturer and the energy saving direct profit does not. Then, the main results are similar to Proposition 4 (a) and Proposition 6 (a). If the total energy cost of the manufacturer is relatively high, the optimal profits of the manufacturer depend on the investment cost factor of the

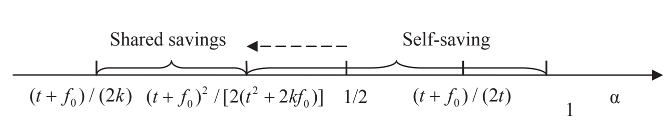


Fig. 3. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer ($t>f_0$,$k>t^2/(t-f_0)$).

manufacturer, the investment cost factor ratio of the ESCO to the manufacturer, and the scaling factor of energy saving effects. Then, the main results are similar to Proposition 4 (b) and Proposition 6 (b).

5. Numerical examples

In this section, we will provide several numerical examples to illustrate our main conclusions (Proposition 3 and Proposition 5 are not included because of their intuition). For common parameters, we assign them as follows: $p_e=r_0=c=1$, $p=5$, $D=100$.When the rates of non-energy benefits returns are extreme values, we have the corresponding mathematical expressions and derive the following figures by Mathematica 9.0. When the rates of non-energy benefits returns are general values, we derive the corresponding figures by Matlab 7.1.

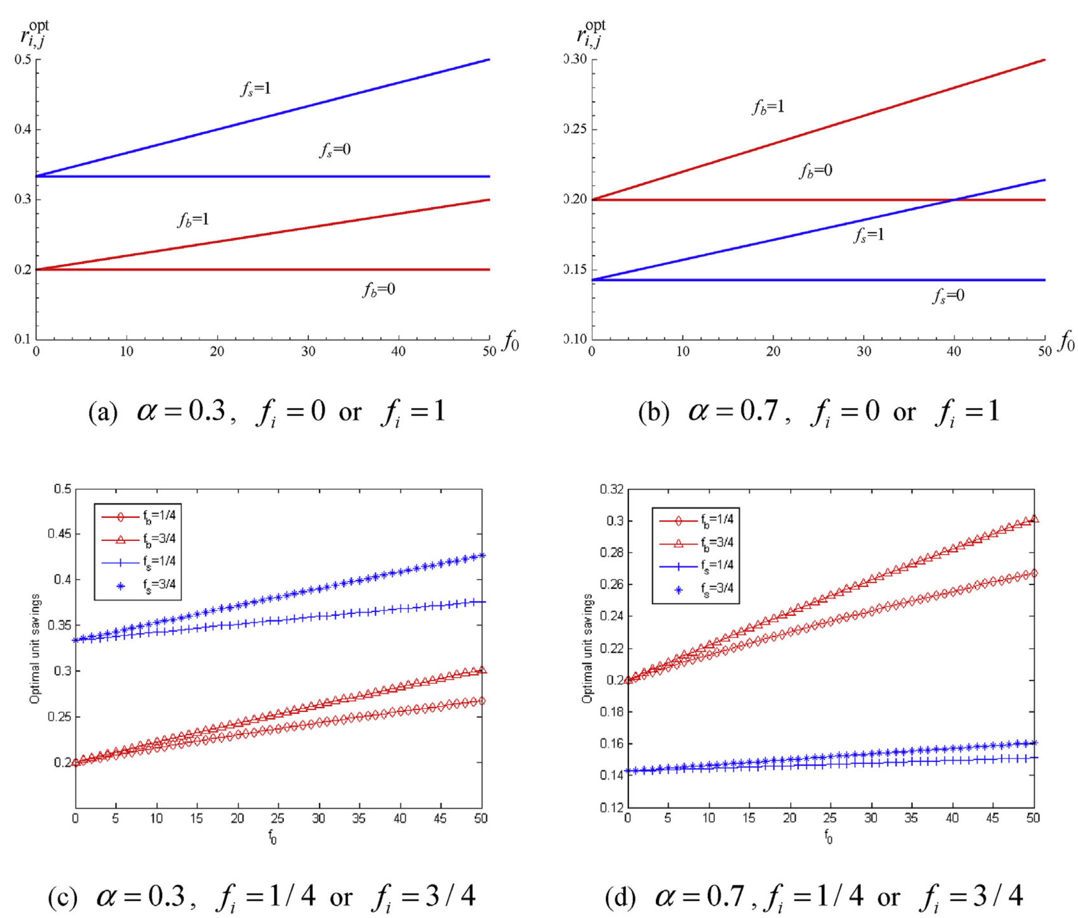
Example 1. In order to illustrate Proposition 1 and Proposition 2, we assume $k=500$, $f_i=0$ or $f_i=1$. $\alpha=0.3(\alpha=0.7)$ represents that the investment cost factor ratio of the ESCO to the manufacturer is small (big). Since the scaling factor of energy saving effects f_0 reflects how much the manufacturer can gain from the non-energy benefits, we assume $0\leq f_0\leq 50$ and analyze the impacts of the scaling factor of energy saving effects f_0 on the optimal unit savings $r_{i,j}^{opt}$ and the optimal profit of the manufacturer $G_{i,j}^{opt}$, as shown as Figs. 4 and 5, respectively.

Observing Figs. 4 and 5, we find that both the optimal unit savings and the optimal profits of the manufacturer are increased with the scaling factor of energy saving effects and considering non-energy benefits increases the motivations of the two companies to improve energy efficiency, which have been shown from Proposition 1 and Proposition 2.

Example 2. In order to illustrate Proposition 4, for $t=100$, if $t\leq\sqrt{2}f_0$, we assume $f_0=80$, if $t>\sqrt{2}f_0$, we assume $f_0=20$. Let $A1=t/(2k)$, $A2=t^2/[2(t+f_0)^2-4(kf_0)]$. Then Fig. 6 provides a "map" of the optimal choice between energy saving modes for the manufacturer in this situation, given the investment cost factor ratio of the ESCO to the manufacturer α and the investment cost factor of the manufacturer k.

Observing Fig. 6(a), we find that the optimal profit of the manufacturer under self-saving is less than the optimal profit of the manufacturer under shared savings and that the manufacturer prefers shared savings, which has been shown as Proposition 4(a). The first part of Proposition 4(b) can be observed from Fig. 6(b). Observing Fig. 6(c), we find that the manufacturer prefers shared savings if $A1<\alpha<A2$ and the manufacturer prefers self-saving if $A2<\alpha\leq 1$, which has been shown as the second part of Proposition 4(b). If $\alpha\leq A1$, because the internal solution r_s does not exist but the internal solution r_b exists, the manufacturer doesn't improve energy efficiency under shared savings and so prefers self-saving.

Example 3. In order to illustrate Proposition 6, for $t=100$, if $t=f_0$, we assume $f_0=100$, if $t>f_0$, we assume $f_0=50$. Let $A3=(t+f_0)/(2k)$, $A4=(t+f_0)^2/[2(t^2+2kf_0)]$. Then Fig. 7 provides a "map" of the optimal choice between energy saving modes for the manufacturer in this situation, given the investment cost factor ratio of the ESCO



'File1.csv here' 'File2.csv here'

Fig. 4. The optimal unit savings vs. the scaling factor of energy saving effects.

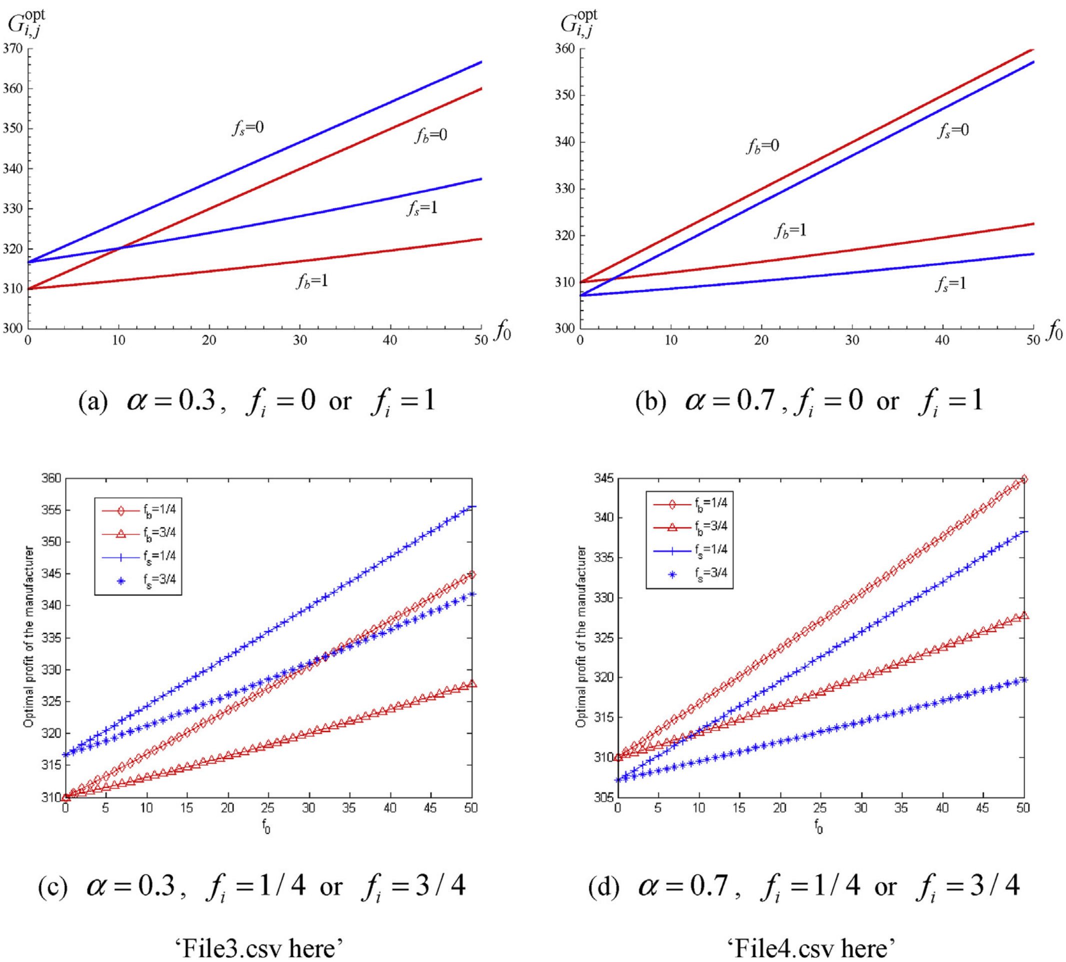


Fig. 5. The optimal profit of the manufacturer vs. the scaling factor of energy saving effects.

to the manufacturer α and the investment cost factor of the manufacturer k.

Observing Fig. 7(a), we find that the optimal profit of the manufacturer under self-saving is more than the optimal profit of the manufacturer under shared savings and the manufacturer prefers self-saving which has been shown as Proposition 6(a). The first part of Proposition 6(b) can be observed from Fig. 7(b). Observing Fig. 7(c), we find that the manufacturer prefers shared savings if $A3<\alpha<A4$ and the manufacturer prefers self-saving if $A4<\alpha\leq 1$, which has been shown as the second part of Proposition 6(b). If $\alpha\leq A3$, the manufacturer prefers self-saving and the reason is the same as Fig. 6.

Example 4. In order to illustrate Proposition 7, three cases $f_b>f_s f_b=f_s f_b<f_s$ will be considered.

(1) if $f_b>f_s$, we assume $f_b=3/4$, $f_s=1/4$; (a) $f_0=200$, $k=500$ represents that the total energy cost to the manufacturer is small; (b) $f_0=20$, $k=700$ represents that both the total energy cost to the manufacturer and the investment cost factor of the manufacturer are big; (c) $f_0=20$, $k=200$ represents that the total energy cost to the manufacturer is big but the investment cost factor of the manufacturer is small. Then the optimal choice between energy saving modes for the manufacturer in this situation is shown as Fig. 8.

Observing Fig. 8, we find that the results shown by Proposition 4 can be extended into the general case ($f_b>f_s$).

(2) if $f_b=f_s$, we assume $f_b=f_s=1/4$ or $f_b=f_s=3/4$, $f_0=50$, $k=500$. Then the optimal choice between energy saving modes in this situation is shown as Fig. 9.

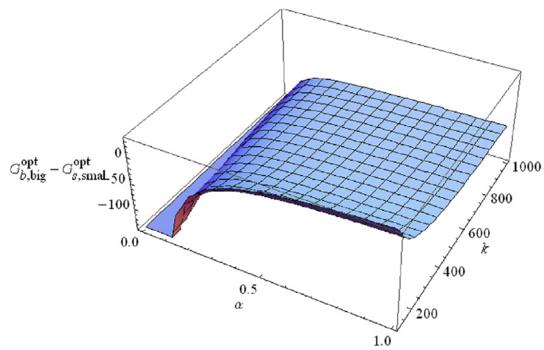
Observing Fig. 9, we find that the results shown by Proposition 5 can be extended into the general case ($f_b=f_s$).

(3) if ($f_b=f_s$), we assume $f_b=1/4 f_s=3/4$; (a) $f_0=200$, $k=500$ represents that the total energy cost to the manufacturer is small; (b)$f_0=20$, $k=150$ represents that the total energy cost to the manufacturer is big but the investment cost factor of the manufacturer is small; (c) $f_0=20$, $k=700$ represents that both the total energy cost to the manufacturer and the investment cost factor of the manufacturer are big. Then the optimal choice between energy saving modes for the manufacturer in this situation is shown as Fig. 10.

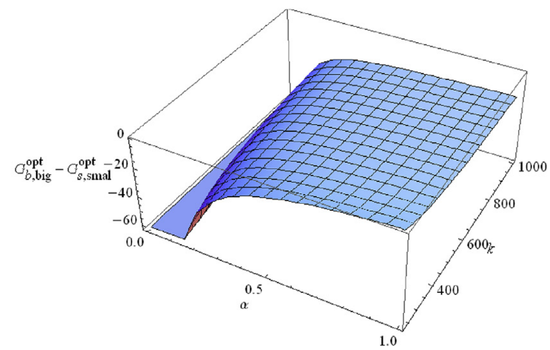
Observing Fig. 10, we find that the results shown by Proposition 6 can be extended into the general case (($f_b<f_s$)).

6. Discussions and implication

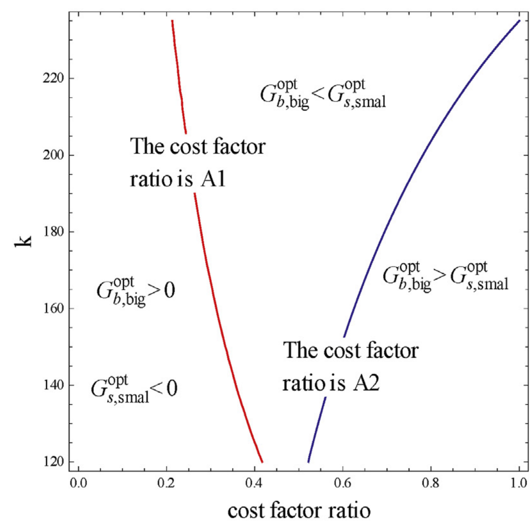
In this section, we first discuss two model assumptions, and then we develop an analytical framework for manufacturers



(a) $t \le \sqrt{2} f_0$, $k > t + f_0$



(b) $t > \sqrt{2} f_0$, $k > [2(t + f_0)^2 - t^2]/(4 f_0)$



(c) $t > \sqrt{2} f_0$, $t + f_0 < k \le [2(t + f_0)^2 - t^2]/(4 f_0)$

Fig. 6. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer and the investment cost factor of the manufacturer (f_b=1,f_s=0).

choosing their optimal energy-saving modes.

6.1. Discussions

6.1.1. The production cost must be significantly affected by improving energy efficiency

In our models, we assume that the unit production cost consists of unit non-energy production cost (see the explanation in Section 3.1) and unit energy cost. Our results are based on the assumption that improving energy efficiency only has an impact on unit energy cost. In practice, the non-energy production cost may be significantly affected by energy efficiency investments, such as frequency conversion equipment that is always used to decrease production setup costs. Assuming the unit non-energy production cost is affected by such investments, we discuss the case. In accordance with the literature (Larsen et al., 2012; Pye and McKane, 2000; Worrell et al., 2003), we divide project savings from energy efficiency projects into energy savings and non-energy benefits (reduced waste, lower emissions, improved maintenance and operating costs, increased production and product quality, an improved working environment and so on). Because the demand is not random, the optimal production quantity is equal to the demand. If the unit non-energy production cost is affected by the investments, the variation in the corresponding revenue can be calculated easily, which is equal to the optimal production quantity multiplied by the variation of unit non-energy production cost. Then, we can integrate the variation in the corresponding revenue into non-energy benefits. If the investments have a negative effect on the unit non-energy production cost, the non-energy benefits will be reduced. On the contrary, the non-energy benefits will be increased. In short, the fact that the production cost must be significantly affected by improving energy efficiency does not affect our results.

6.1.2. How lack of information on non-energy benefits would affect the results

In our models, assuming that the information on non-energy benefits is adequate, we obtain the related parameters of non-energy benefits and precisely calculate the non-energy benefits. In practice, we may lack information on non-energy benefits. Insufficient information leads to uncertainty about the related parameters of non-energy benefits, for example, the scaling factor of energy saving effects f_0. In the following, we discuss how the uncertainty of the scaling factor of energy saving effects can affect our results. Let the scaling factor of energy saving effects $f_0' = f_0 + \varepsilon$, where ε is a random variable defined in [-x,x]($x \ge 0$) with zero mean

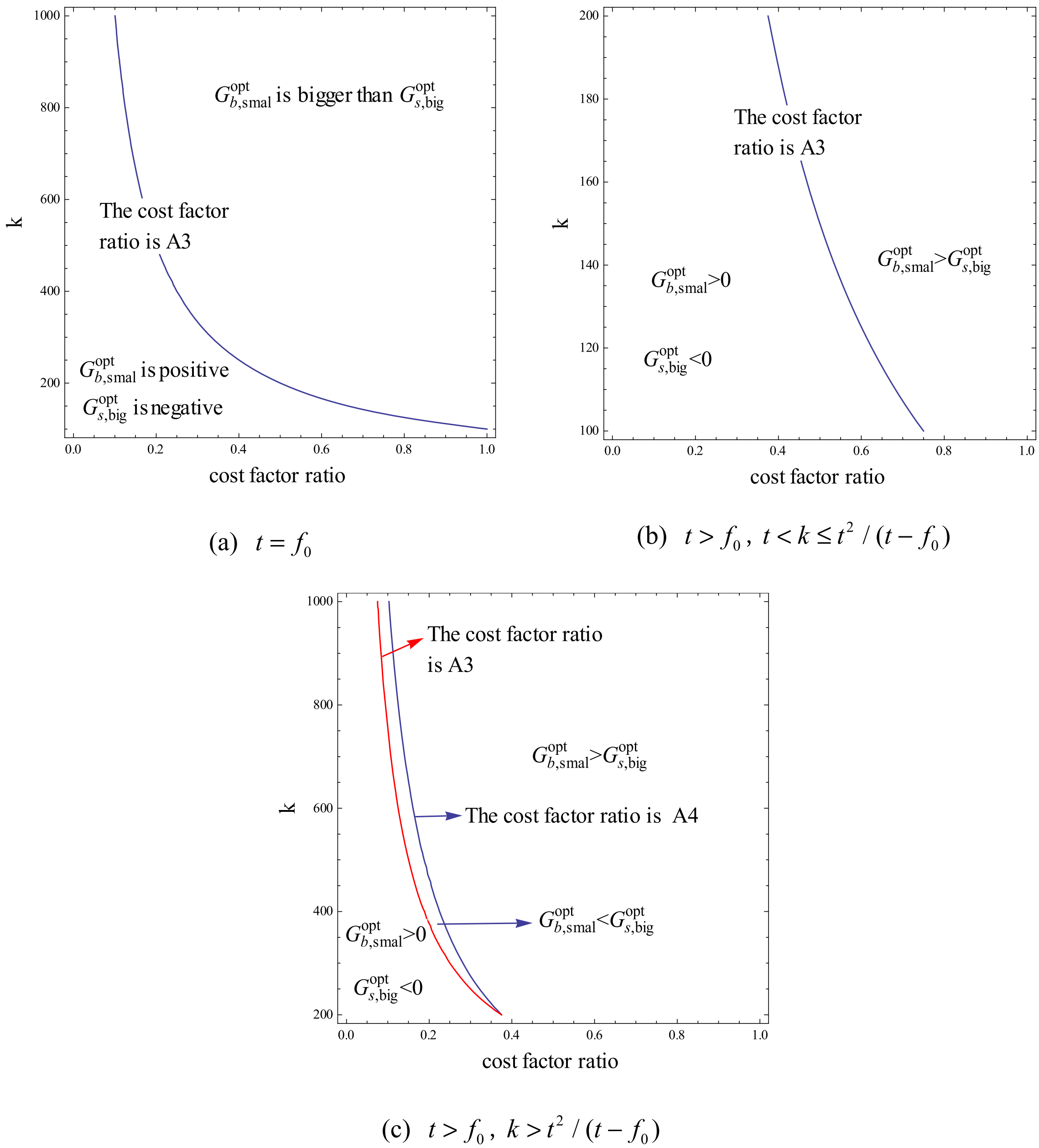


Fig. 7. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer and the investment cost factor of the manufacturer (f_b=0,f_s=1).

and variance σ^2. The random variable ε (explained as a disturbance factor) is realized after operating energy efficiency projects, but the choice between energy saving modes must be made during the audit or the design phrases. Then, the manufacturer determines the optimal choice between energy saving modes by comparing the optimal expected profits during the audit or the design phrases. If the manufacturer chooses self-saving, substituting f_0' for f_0 in profit function (1) we obtain the expected profit function of the manufacturer. For $E(f_0') = f_0$, we expect the above expected profit function and have the same profit function as (1) under the uncertainty of the scaling factor case. Then, this indicates that the results under the uncertainty of the scaling factor case are not changed when self-saving is chosen. Similarly, we can know that the uncertainty of the scaling factor has no impact on the results when shared savings is chosen. In short, lack of information on non-energy benefits may not affect our results and our results only depend on the mean values of the related parameters of non-energy benefits.

The accuracy of calculating non-energy benefits depends on the specification of the calculation methodology. Regarding how to calculate non-energy benefits, we can learn from Mills and Rosenfeld (1996) and Worrell et al. (2003). We can divide the calculation methodology into two steps, i.e., identifying and describing non-energy benefits associated with a given measure and quantifying non-energy benefits as much as possible. In the first step, given a measure, we list all the significant impacts aside from energy savings, which should be described as specifically as possible (Worrell et al., 2003). In the second step, the non-energy benefits identified above should be quantified in the most direct terms by with and without comparison analysis (Mills and Rosenfeld, 1996).

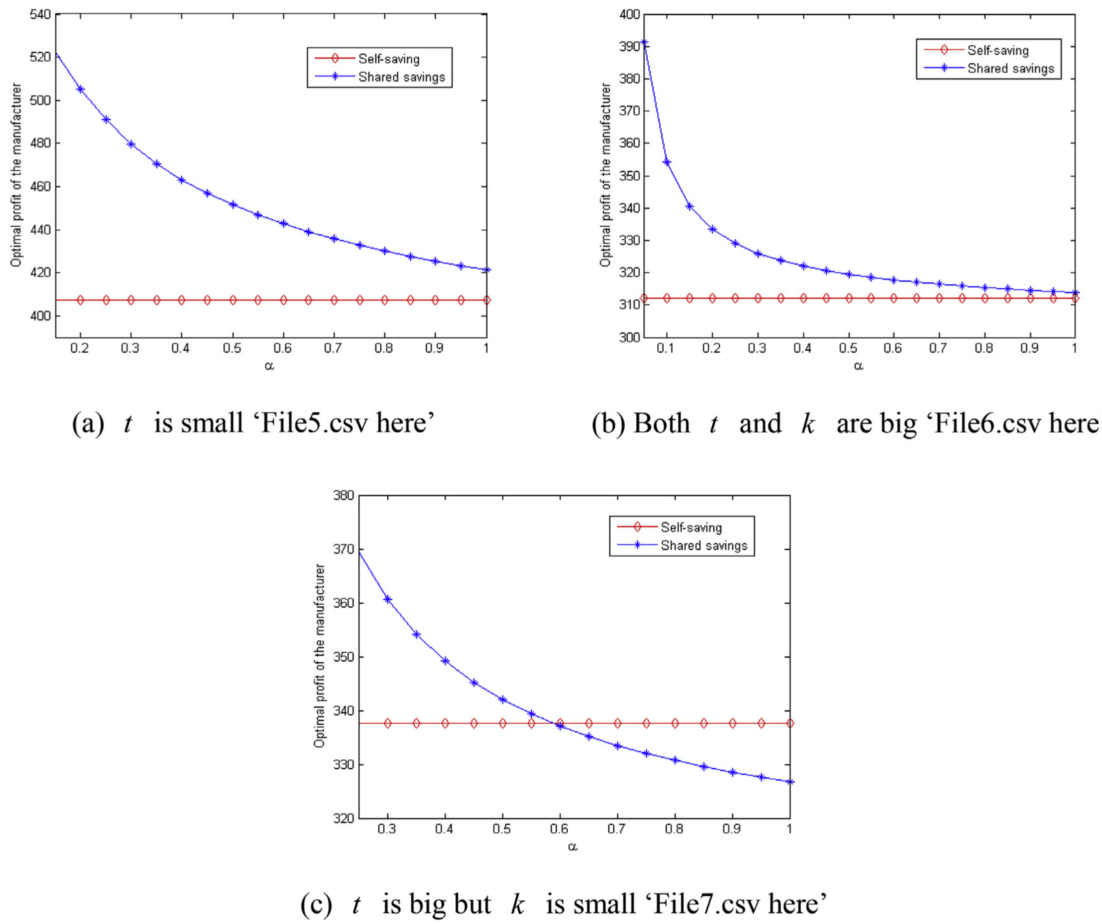


Fig. 8. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer ($f_b > f_s$).

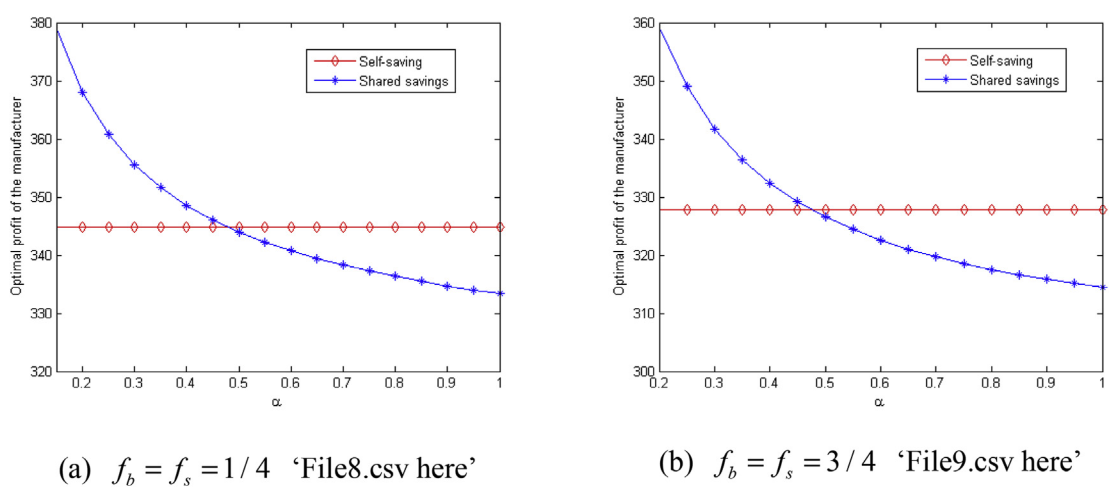
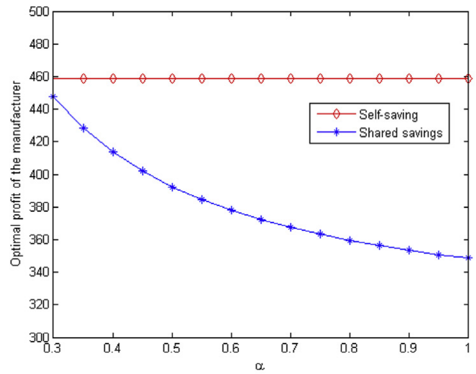


Fig. 9. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer ($f_b = f_s$).

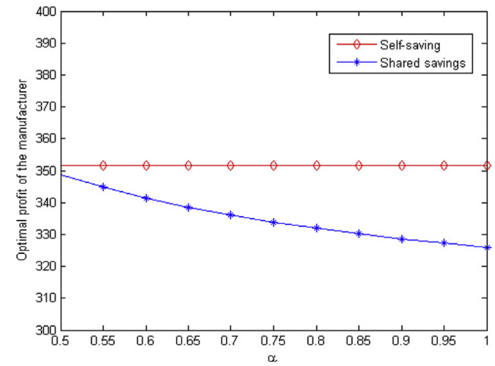
6.2. Implication

To facilitate the application of our findings, we propose an analytical framework for manufacturers choosing their optimal energy-saving modes. The entire analytical framework is divided into four steps, i.e., identify whether the conditions satisfy the main model assumptions, estimate the model parameters, choose the optimal energy saving mode for the manufacturer by corresponding propositions and determine the optimal decisions of the manufacturer based on the optimal energy saving mode, as shown in Fig. 11.

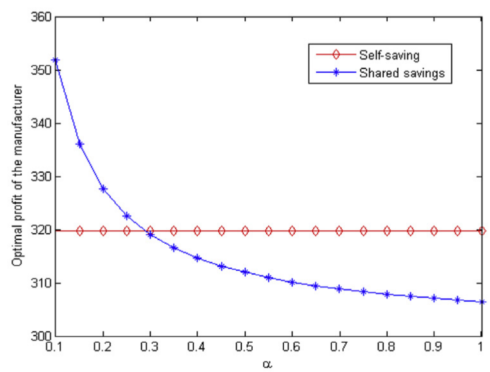
In the first step, we verify five main model assumptions (see Table A1). In the second step, we mainly estimate model parameters, such as p, c, r_0, D and so on (see Table A2). In the third step,



(a) t is small ‘File10.csv here’



(b) t is big but k is small ‘File11.csv here’



(c) Both t and k are big ‘File12.csv here’

Fig. 10. The optimal choice between energy saving modes vs. the investment cost factor ratio of the ESCO to the manufacturer ($f_b<f_s$).

according to whether non-energy benefits are considered or not, we discuss two cases including considering only energy savings ($f_0=0$) and considering non-energy benefits ($f_0>0$). Furthermore, we divide considering non-energy benefits ($f_0>0$) into four cases, i.e., the rate of non-energy benefits returns under self-saving is higher than the rate of non-energy benefits returns under shared savings ($f_b=1$,$f_s=0$); the rates of non-energy benefits returns under two energy saving modes are equal ($f_b=f_s=0$ or 1); the rate of non-energy benefits returns under self-saving is smaller than the rate of non-energy benefits returns under shared savings ($f_b=0$,$f_s=1$); and the general case ($f_b \neq f_s \in (0,1)$) and derive Propositions 3–7. We list the six conditions under which the optimal energy saving mode is chosen in Fig. 11 (see Table A3). From conditions 1–6, the manufacturer can choose the optimal energy saving mode. In the last step, given an energy saving mode, the manufacturer can determine the optimal decisions from Table 1.

7. Conclusions and future research

Energy conservation has grown up to be an important and effective means for energy-intensive manufacturers to improve their competitiveness. Facing various energy saving modes in practice, manufacturers have to choose their optimal energy saving modes. In this paper, we discuss an energy-intensive manufacturer facing self-saving and shared savings options and how this manufacturer chooses the optimal energy saving mode when non-energy benefits are considered. Our results give some important managerial insights for the business executives on how to choose the optimal energy saving modes. The main conclusions are as follows.

Considering only energy savings, we find that the optimal unit savings has a monotonic impact on the optimal profit of the manufacturer. Furthermore, we show that the investment cost factor ratio of the ESCO to the manufacturer is a key factor which has a strong impact on the choice between energy saving modes. When the investment cost factor ratio is small, the manufacturer will prefer shared savings. Otherwise, the manufacturer will prefer self-saving.

When non-energy benefits are considered, we have the following results.

(1) We theoretically demonstrate the empirical result (Worrell et al., 2003; Pye and McKane, 2000), i.e., considering non-energy benefits increases motivation to improve energy efficiency and increases the optimal profits for two companies.
(2) When the rates of non-energy benefits returns under the two energy saving modes are equal, the main results are similar to considering only energy savings case.
(3) When the rate of non-energy benefits returns under self-saving is bigger (smaller) than the rate of non-energy benefits returns under shared savings, the result that the optimal unit savings has a monotonic impact on the optimal profit of the manufacturer is not correct. Furthermore, unlike the above results, the choice of energy saving modes not only depends on the investment cost factor ratio of the ESCO to the manufacturer but also depends on the total energy cost to the manufacturer, the investment cost factor of the

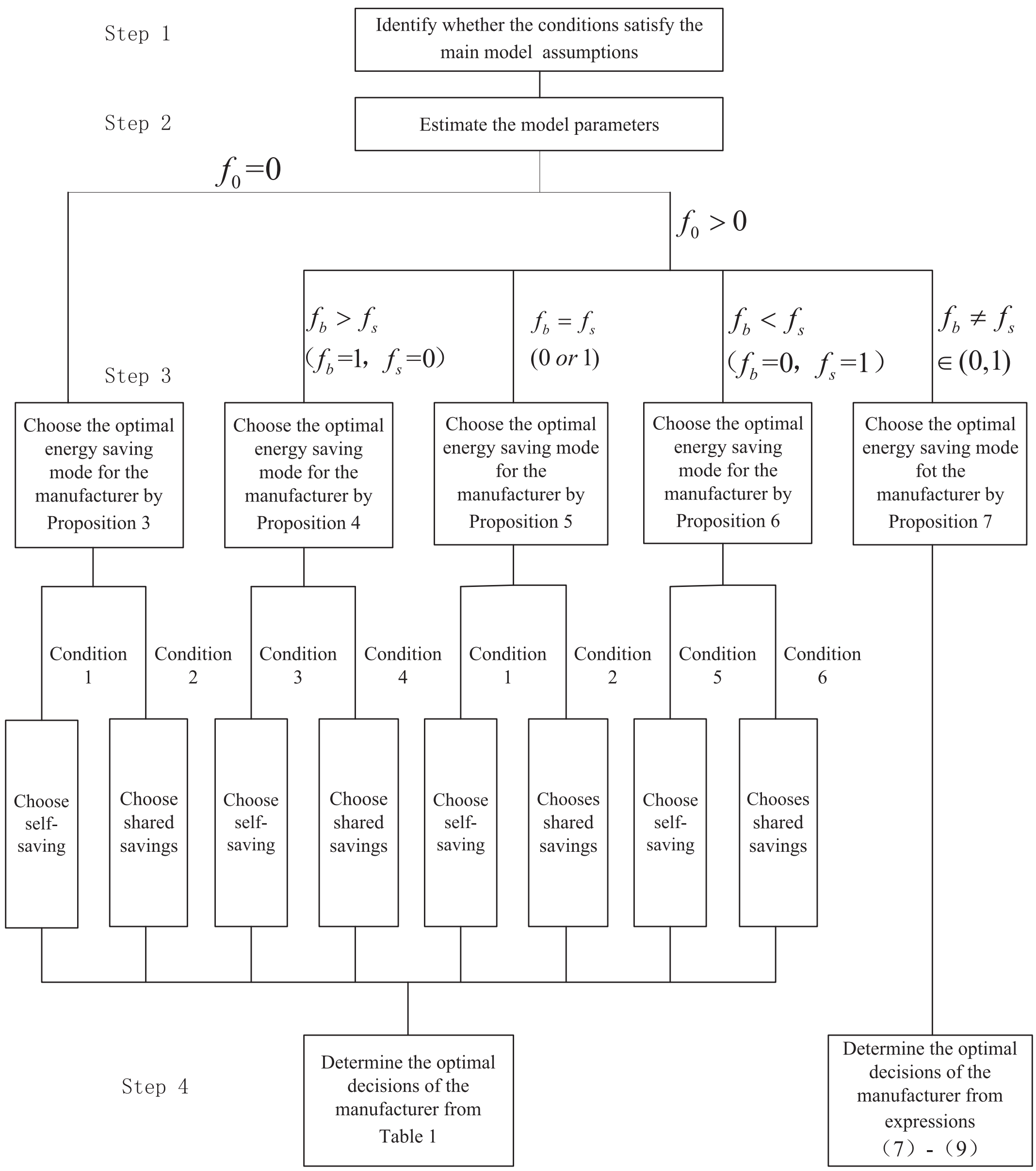


Fig. 11. The analytical framework for choosing the optimal energy saving mode.

manufacturer and the scaling factor of energy saving effects. Moreover, the range in which self-saving is chosen is narrowed (expanded).

There are several limits in our models. First, the energy prices are random in practice and it is very interesting that the uncertainty of energy prices is integrated into our models. Second, other energy saving modes exist in practice, such as guaranteed savings, leases and so on. When considering other energy saving modes, how to choose their optimal energy saving modes for manufacturers is also a very real problem. Third, we only consider "costs and profit" as non-energy benefits. However, there are other different non-energy benefits, such as quality and waste flows and so on. How to link different models on different non-energy benefits is also an important problem.

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Appendix C. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.08.142.

Appendix A

Proposition A.1 Given self-saving and shared savings, assuming$f_0>0$ and $f_b>f_s$($f_b=1,f_s=0$),

①if $t/(2k)<\alpha<t/[2(t+f_0)]$, $r^*_{s,sma} > r^*_{b,big}$;
②if $\alpha=t/[2(t+f_0)]$, $r^*_{s,sma} = r^*_{b,big}$;
③if $t/[2(t+f_0)]<\alpha\le 1$, $r^*_{s,sma} < r^*_{b,big}$.

Proposition A.2 Given self-saving and shared savings, assuming$f_0>0$ and $f_b<f_s$($f_b=0,f_s=1$),

①if $(t+f_0)/(2k)<\alpha<(t+f_0)/(2t)$, $r^*_{s,big} > r^*_{b,sma}$;
②if $\alpha=(t+f_0)/(2t)$, $r^*_{s,big} = r^*_{b,sma}$;
③if $(t+f_0)/(2t)<\alpha\le 1$, $r^*_{s,big} < r^*_{b,sma}$.

Appendix B

Proof of Proposition 3. Let $\Delta\prod_1 = \prod_{ms}(\varphi^*_{no}) - \prod_{mb}(r^*_{b,no})$, we have $\Delta\prod_1=t^2(1-2\alpha)/(4\alpha k)$, and we easily know that the sign of the above expression depends on $1-2\alpha$. From Table 1, we get $k>t$, $\alpha>t/(2k)$. For $t/(2k)<1/2$, the proof is completed.

Proof of Proposition 4. For$\Delta\prod_2 = \prod_{ms}(\varphi^*_{sma}) - \prod_{mb}(r^*_{b,big}) = [t^2 - 2\alpha((t+f_0)^2 - 2kf_0)]/(4\alpha k)$, if $k\ge(t+f_0)^2/(2f_0)$ k, we have $\Delta\prod_2>0$. From Table 1, we have $k>t+f_0$ and $t/(2k)<\alpha\le 1$. If $t\le f_0$, for $k>t+f_0\ge(t+f_0)^2/(2f_0)$, we have $\Delta\prod_2>0$. Then if $k>t+f_0$ and $t/(2k)<\alpha\le 1$, we have $\prod_{ms}(\varphi^*_{sma}) > \prod_{mb}(r^*_{b,big})$. If $f_0<t\le 2f_0$, for $t+f_0<(t+f_0)^2/(2f_0)$, when $k\ge(t+f_0)^2/(2f_0)$, we have $\prod_{ms}(\varphi^*_{sma}) > \prod_{mb}(r^*_{b,big})$. When $t+f_0<k<(t+f_0)^2/(2f_0)$, let $t^2-2\alpha(t+f_0)^2-2kf_0)=0$, we get $\alpha=t^2/[2(t+f_0)^2-4kf_0)]$. For $t \le \sqrt{2}f_0$, we have $t+f_0>[(t+f_0)^2-t^2/2]/(2f_0)$ and $t^2/[2(t+f_0)^2-4kf_0)]>1$. If $t+f_0<k<(t+f_0)^2/(2f_0)$, we also have $\prod_{ms}(\varphi^*_{sma}) > \prod_{mb}(r^*_{b,big})$. Summarizing the above analysis, we have Proposition 4(a). If $t>2f_0$, $(t+f_0)^2/(2f_0)>[(t+f_0)^2-t^2/2]/(2f_0)>t+f_0$. When $k\ge(t+f_0)^2/(2f_0)$, we have $\prod_{ms}(\varphi^*_{sma}) > \prod_{mb}(r^*_{b,big})$. When

Table A1
The main model assumptions.

Assumption 1	The manufacturer is perfect monopolistic;
Assumption 2	The demand is not random and the retail price of the product is fixed;
Assumption 3	Both of the manufacturer and the ESCO maximize private profits;
Assumption 4	Both of the manufacturer and the ESCO are risk-neutral and information is completely symmetrical;
Assumption 5	The manufacturer, as a leader, and the ESCO as a follower have a Stackelberg game.

Table A2
Decision variables and model parameters.

Decision variables	
r_b	Unit savings when self-saving is chosen under the general case;
r_s	Unit savings when shared savings is chosen under the general case;
φ	Fraction of unit savings when shared savings is chosen under the general case;
$r_{i,j}$	Unit savings when *i* energy saving mode is chosen under *j* case;
φ_j	Fraction of unit savings when *i* energy saving mode is chosen under *j* case.
Model parameters	
p	Retail price of the product;
c	Unit non-energy production cost;
r_0	Unit's initial energy level;
p_e	Energy price;
D	Demand;
f_0	Scaling factor of energy saving effects;
f_i	Rate of non-energy benefits returns;
k	Investment cost factor;
T_s	Agreed contract term;
t	Total energy costs before improving energy efficiency;
A	Profit of the manufacturer before improving energy efficiency;
ε	Disturbance factor of the scaling factor of energy saving effects;
$\prod_{mb}(r_b)$	Profit of the manufacturer when self-saving is chosen;
$\prod_{ms}(\varphi)$	Profit of the manufacturer when shared savings is chosen;
$\prod_{es}(r_s)$	Profit of the ESCO when shared savings is chosen.

Notes: subscripts b,s represent that the manufacturer chooses self-savings and shared savings respectively; j=*no,sma, big* represent that only energy savings are considered ($f_0=0$), the rates of non-energy benefits returns are small when non-energy benefits are considered ($f_0>0,f_i=0$), and the rates of non-energy benefits returns are big when non-energy benefits are considered ($f_0>0,f_i=1$), respectively.

Table A3
The conditions under which the optimal energy saving mode is chosen.

Condition 1	$1/2<\alpha\le 1$
Condition 2	$t/(2k)<\alpha<1/2$
Condition 3	$t>2f_0$, $t+f_0<k\le[2(t+f_0)^2-t^2]/(4f_0)$, $t^2/[2(t+f_0)^2-4kf_0)]<\alpha\le 1$
Condition 4	$t \le \sqrt{2}f_0$ or $t > \sqrt{2}f_0$ and $k>[2(r+f_0)^2-t^2]/(4f_0)$ or $t > \sqrt{2}f_0$, $t+f_0<k\le[2(t+f_0)^2-t^2]/(4f_0)$ and $t/(2k)<\alpha<t^2/[2(t+f_0)^2-4kf_0]$
Condition 5	$t=f_0$ or $t>f_0$ and $t<k\le t^2/(t-f_0)$ or $t>f_0$, $k>t^2/(t-f_0)$ and $(t+f_0)^2/[2(t^2+2kf_0)]<\alpha\le 1$
Condition 6	$t>f_0$, $k>t^2/(t-f_0)$ and $(t+f_0)/(2k)<\alpha<(t+f_0)^2/[2(t^2+2kf_0)]$

$[(t+f_0)^2-t^2/2]/(2f_0)<k<(t+f_0)^2/(2f_0)$, for $t^2/[2(t+f_0)^2-4kf_0)]>1$, we also have $\prod_{ms}(\varphi^*_{sma})>\prod_{mb}(r^*_{b,big})$. Then, we have Proposition 4(i). When $t+f_0<k\leq[(t+f_0)^2-t^2/2]/(2f_0)$, for $t/(2k)<t^2/[2(t+f_0)^2-4kf_0)]\leq 1$, we have Proposition 4 (ii). The proof is completed.

Proof of Proposition 5. Let $\Delta\prod_3=\prod_{ms}(\varphi^*_{sma})-\prod_{mb}(r^*_{b,sma})$, $\Delta\prod_4=\prod_{ms}(\varphi^*_{big})-\prod_{mb}(r^*_{b,big})$. From Table 1, we have $\Delta\prod_3=\Delta\prod_1$, $\Delta\prod_4=(t+f_0)^2(1-2\alpha)/(4\alpha k)$. The signs of $\Delta\prod_3$ and $\Delta\prod_4$ are same as $\Delta\prod_1$, which are decided by $1-2\alpha$. The proof is completed.

Proof of Proposition 6. For $\Delta\prod_5=\prod_{ms}(\varphi^*_{big})-\prod_{mb}(r^*_{b,big})=[(t+f_0)^2-2\alpha(t^2+2kf_0)]/(4\alpha k)$, we easily know $t\geq f_0$, $k>t$, $\alpha>(t+f_0)/(2k)$, then we have $2(t^2+2kf_0)-(t+f_0)^2>0$, i.e., $(t+f_0)^2/[2(t^2+2kf_0)]<1$. If $t=f_0$, then we have $(t+f_0)/(2k)>(t+f_0)^2/[2(t^2+2kf_0)]$. When $(t+f_0)/(2k)<\alpha\leq 1$, $\prod_{ms}(\varphi^*_{big})<\prod_{mb}(r^*_{b,sma})$, Proposition 6 (a) is proved. If $t>f_0$, when $k>t^2/(t-f_0)$, we have $(t+f_0)^2/[2(t^2+2kf_0)]>(t+f_0)/(2k)$, then we get Proposition 6(ii). When $t<k\leq t^2/(t-f_0)$, $(t+f_0)^2/[2(t^2+2kf_0)]\leq(t+f_0)/(2k)$, for$(t+f_0)/(2k)<\alpha\leq 1$, then $\prod_{ms}(\varphi^*_{big})<\prod_{mb}(r^*_{b,sma})$, Proposition 6 (i) is proved.

Proof of Proposition A.1. From Table 1, we have $r^*_{s,sma}-r^*_{b,big}=r_0[t-2\alpha(t+f_0)]/(2\alpha k)$. For $\alpha>t/(2k)$,$k>t+f_0$, $t/(2k)<t/[2(t+f_0)]<1/2$. If $t/(2k)<\alpha<t/[2(t+f_0)]$, we get $r^*_{s,sma}>r^*_{b,big}$. The other parts of Proposition A.1 are easily proved.

Proof of Proposition A.2. From Table 1, we have $r^*_{s,big}-r^*_{b,sma}=r_0(t+f_0-2\alpha t)/(2\alpha k)$. From Table 1, we get $k>t$,$t\geq f_0$,$\alpha>(t+f_0)/(2k)$, then $(t+f_0)/(2k)<(t+f_0)/(2k)\leq 1$. If $(t+f_0)/(2k)<\alpha<(t+f_0)/(2k)$, We have $r^*_{s,big}>r^*_{b,sma}$. The other parts of Proposition A.2 easily are proved.

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