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An Energy Performance Contract Optimization Approach to Meet the Competing Stakeholder Expectations under Uncertainty: A Canadian Case Study

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Abstract: Energy performance contracts (EPC) can address economic sustainability challenges associated with residential energy retrofitting projects, including funding limitations, poor quality of project delivery, and landlord-tenant dilemma. Literature has overlooked the impact of weighted average cost of capital (WACC) and funding sources in EPC planning. However, the WACC, stakeholder priorities, and uncertainties can alter the project outcomes. This study proposes a Monte-Carlo simulation based non-linear multi-objective optimization approach to address the aforementioned challenges. A case study conducted in British Columbia indicated that the maximum overall project profitability can vary between \$18,035 and \$20,626 with decision priorities. The overall project profitability can vary over 9% due to uncertainties. The project profits can change over \$3000 due to changes in the WACC. These observations confirmed the criticality of accounting for WACC, stakeholder priorities, and uncertainties in EPC planning. The risk of compensating for the performance compromises and profits increases simultaneously for the energy services company with the increasing contract periods, while it is inverse for the owners. Therefore, the contract period must be decided considering the profit expectations and risk tolerance of the stakeholders. Extended contract periods allow lower capital contributions from the building owners, potentially solving the principal-agent disputes in rental buildings.

Keywords: energy performance contract; energy retrofit; multi criteria decision making; Monte Carlo simulation; energy simulation



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1. Introduction

There are ongoing global warming and climate change mitigation efforts all around the world with increasing awareness and appreciation of potential environmental risks. Inter-governmental panel on climate change (IPCC) emphasized the need for maintaining the global temperature increment below 1.5 °C compared to pre-industrial times to avoid future adversities [1]. Buildings are responsible for 12% and 40% of the global greenhouse gas (GHG) emissions and energy use, respectively [2,3]. Therefore, IPCC identified the building sector as a key area that needs attention in achieving the emissions reduction targets established to control the global temperature [1].

Aligning with the global efforts, North American and Canadian climate leaders such as the Government of British Columbia (BC) have proposed innovative energy efficiency standards such as BC Energy Step Code (BC-ESC) for new constructions [4]. BC-ESC has a structured process, clearly defining the performance steps that buildings need to achieve in the construction phase. This approach seems to have promising energy efficiency enhancement potential. However, there are no such comprehensive energy efficiency standards developed for existing residential buildings, especially in BC and Canada [5]. The global rates of new constructions are recorded to be less than 1% and 10% on average in cities and booming areas, respectively [6]. There are 14.1 million existing residential

buildings in Canada, accounting for 17% of the total GHG emissions of the country, and there lies a significant energy and emissions saving potential [6,7]. These buildings have not been constructed according to stringent energy efficiency guidelines in the construction phase except for the most recent ones. Moreover, the condition of existing buildings in Canada is reported to be deteriorating [8]. Therefore, it is essential to devise strategies to enhance the energy and environmental performance of existing buildings in order to meet Canadian climate action goals. Some incentive and rebate schemes have already been implemented in Canada by government organizations and non-government organizations such as utility providers to promote energy retrofit projects [5]. However, the principal-agent problems in rental buildings, inability to gather the required capital investments, awareness issues, and lack of investor confidence are still not adequately resolved [5,9,10]. Innovative financing mechanisms, financial and operational risk mitigation approaches, marketing campaigns, and awareness programs can support addressing the discussed issues in promoting energy efficiency for older buildings.

Energy service companies (ESCO) provide financial risk mitigation models such as energy efficiency insurances and energy performance contracts (EPC), which can be used to address the operational and financial risks faced by the owners employing means such as guaranteed savings [10]. Generally, ESCOs focus on bigger buildings such as multi-unit residential buildings (MURB), commercial buildings, and building clusters owned by institutions [11]. These projects involve high investments and returns, which motivate both building owners and the ESCOs to be involved. New ESCOs and smaller players have challenges in financing large-scale projects [11]. Some literature suggests that EPCs are less successful in small-scale residential projects unless tied with other service agreements such as repair and maintenance [12]. Developing a workable EPC model for the residential sector can provide an opportunity for small-scale entrepreneurs to enter the energy services market [11] and mitigate the challenges faced by building owners in acquiring capital investments for energy efficiency projects while managing financial and operational risks [13]. On the other hand, successful EPCs can produce energy and emissions savings. For example, some EPC ventures have reportedly improved the energy efficiency of the buildings that underwent renovations by 22–45% [14]. On the other hand, the involvement of an ESCO in a renovation project can boost investors' confidence and resolve principal agent problems leading to wider community penetration of building energy retrofits. Moreover, it is likely that the quality of the retrofitting process is maintained at the best possible level by the ESCO as it profits from the energy savings produced during the contract period. Therefore, this is a topic worthy of investigation from both financial and environmental viewpoints.

According to a recent Danish study, supporting tools and finances related to EPCs are stuck in a deadlock as one cannot proceed without the other aspect being improved [15]. Supporting information needs to be provided to the investors through research studies, because money is less likely to flow into an area where investor confidence is low. Therefore, financial models and support tools need to be developed as the first step towards successful community penetration of EPCs and energy retrofits focused on residential buildings. With this understanding, the authors conducted a comprehensive literature review to identify the potential challenges, opportunities, and support tools for introducing EPCs for the residential market.

A keyword search including “residential building” and “energy performance contract” terms recorded 42 research items in the “Compendex Engineering Village” database. Out of the 42 articles, 37 research articles published after 2000 were considered for the study to maintain the timeliness of the discussion. This included ten journal articles, fourteen conference articles and ten conference proceedings, two standards, and a book chapter. A manual screening was done to assess the relevance of the search results to energy performance contracting in residential buildings. The filtered articles were reviewed in detail to understand the current research landscape around the topic. The findings from

the literature review, which lead to the research gaps in the current body of knowledge are presented in the coming sections.

1.1. Challenges for Energy Performance Contracting

This section discusses the key challenges and potential solutions for EPCs in reference to literature.

1.1.1. Financing and Awareness Issues

Energy retrofit projects include multiple players, including the building owners and tenants, contractors and ESCOs, and third-party incentive providers such as government bodies and utility providers. Depending on the employed project delivery model, some or all of these players may have a role in financing a given energy retrofit project. This section discusses the financial challenges specific to different players and the energy retrofitting projects in general.

High transaction costs are a barrier faced when forming EPCs for residential buildings [16,17]. These transaction costs can include marketing, documentation, legal fees, and other similar costs. Lack of building owner awareness is a barrier in reducing the transaction costs [18]. Innovative communication and marketing methods have the potential to minimize the high transaction costs [18,19]. Cooperative advertisement strategies among the stakeholder groups, including the government organizations, utility providers, and ESCOs, is a potential approach proposed to reduce transaction costs [20]. The retrofit promotions and incentive programs operated by the government and non-government organizations can communicate the potential benefits of EPCs to the community. As of now, CleanBC (a government organization in Canada) communicates the incentives available for residential building energy retrofit projects from CleanBC, other government bodies (municipalities), and non-government bodies (utility providers). If the information related to EPCs can also be communicated to the community by these already established and trusted communication channels the ESCOs can penetrate the market and reduce the transaction costs simultaneously. On the other hand, operations and promotion of ESCOs can easily act as community awareness boosters about the benefits of the retrofits and available incentive programs executed by other organizations [14].

Budget constraints are another key challenge faced by the building owners. This has been addressed in Europe by means such as government subsidies and low-interest loans. Russia has introduced a preferential loan scheme to overcome the investment challenges for the residential building retrofitting projects [14]. Relatively higher leverage and trust ESCOs can gain from the financial institutes such as banks in securing low-interest loans can help the building owners to overcome initial budget barriers [16]. However, having to provide a significant portion of the capital and lack of assets to tie the contracts for long time periods pose challenges for residential EPCs [21]. Moreover, loans bind the ESCOs to long-term financial commitments with third-party financial institutes, thus limit the financial freedom and the ability to commit to new projects. The potential of selling the energy performance contracts as assets at a profit to improve the company equity was proposed as a solution for this issue [22]. Moreover, entering into legal bonds to pay off the remaining capital investment using the increased property resale value has been proposed to address the potential challenges created by changing the ownership.

The retrofit implementation costs can be brought decreasing the number of retrofit projects allowing the suppliers to enter into mass-production opportunities [22]. Diversifying the ESCO business model can also increase the profitability of the projects. For example, if a renovation company simultaneously plays the role of an ESCO, it allows the company to benefit from the profits obtained from the renovation project and the cost savings realized during the operational phase. Moreover, it allows the company to attract more renovation projects as it supports the project financing and operations and maintenance work [23]. Positively using the leverage an ESCO has over its' staff, a UK-based company promised a shared bonus scheme for the trades workers, which helped improve

the quality and efficiency of the work while simultaneously reducing the project costs [18]. Therefore, it is evident that high-quality project delivery and proper coordination between the contractors can be easily ensured by ESCOs using innovative management strategies. Therefore, additional non-energy benefits such as improved property values, rental price increases, and thermal comfort improvements can be successfully achieved by introducing EPCs to the renovation projects.

1.1.2. Principal-Agent Issues

Even after a viable financing plan has been developed, uneven costs and benefits distribution among the stakeholders can challenge the progress of retrofit projects. This is identified as the principal-agent problem or split-incentive issue. This phenomenon can be more prevalent in rental properties and referred to as the landlord-tenant dilemma [15]. When the tenants are responsible for the utility bills, building owners are not motivated to improve the energy efficiency of rental buildings as direct financial benefits for the owners are not clear. Landlords receive indirect benefits from the retrofitting projects in the form of increased property resale value and increased rental income when re-renting. However, these indirect benefits seem to be insufficient to motivate the landlords to investment in retrofits. On the other hand, tenants are reluctant to invest in rental property renovations. Therefore, promoting energy retrofits in rental properties sector is a challenge.

The green lease approach is identified as a potential agreement between the building owners and tenants to split the incentives of the retrofitting projects. In this approach, the building owner invests the initial capital, which is recouped by a pre-agreed rental increase. The tenants are going to be compensated for the increased rental by the subsequent operational cost savings due to the increased energy efficiency [15]. Even though this model seems to be a fair to solution to the landlord-tenant dilemma, current tenancy laws in BC, Canada, can question the rental increases. Even if the tenancy laws are modified, the landlords and tenants doesn't have the expertise to formulate a green lease. For example, determining the investments attributable for energy efficiency upgrades in a renovation project, quantifying the performance risks, and determining an appropriate rental increase need expert inputs from field experts such as ESCOs.

ESCOs can formulate fair EPCs and support the building owner in securing third-party loans, reducing the associated split-incentive issues. This minimizes the capital cost requirement from the owner and increases the ESCO's potential to secure a higher profit share while offering the tenants some cost savings. This approach unites the ESCO and the tenants/occupants for the common goal of energy and cost savings, which can help instill energy-conscious behavior among the building occupants. In summary, an ESCO can work as an intermediate partner to communicate between stakeholders and provide a savings guarantee for the tenants while finding third-party funding sources to support the building owners. However, identifying the optimal capital contributions and the profit split between the stakeholders and the contract periods is crucial in solving the said issues via EPCs.

1.1.3. Design-Performance Gap

In some energy efficiency projects, anticipated energy efficiency improvements in the design stage are not realized in actual operations due to data unavailability, and inaccuracies and uncertainties in performance predictions. This is commonly referred to as the design-performance gap [18]. Lack of awareness of the occupants about how to achieve the best possible energy savings in the operational stage by following energy-conscious behavior and using newly implemented technical solutions in buildings can also contribute to the design-performance gap [23,24].

Performance Prediction Errors

Energy monitoring and deemed savings approaches are commonly used in retrofit project evaluations [20]. Deemed savings are subjectively decided by the energy experts

based on previous experience or energy simulation-based predictions. Monitoring-based approaches determine the savings based on monitored data. Both approaches have their own advantages and disadvantages.

The deemed savings approach can be effective when experts are involved and the project focusses on well-known retrofits. However, expert judgments may fail to accurately quantify the operational uncertainties specific to a given project and predict the performance of the novel upgrades. Even simulation-based approaches may pose inaccuracies due to unrealistic underlying assumptions and inaccuracies in input data [24]. However, the deemed savings approach requires no additional instrumentation, thus saves the instrumentation cost allowing to maximize the profit margin of an EPC.

Energy monitoring can improve the accuracy of performance predictions and help resolve design-performance gap related EPC disputes [17,25,26]. The accuracy of the predictions can be further improved by integrating the energy monitoring, performance simulation, and data analytics [25]. Redundant use of sensors can be minimized by employing innovative approaches such as calibrated energy simulations [27], advanced uncertainty handling techniques, and occupant-based energy use prediction models [23] parallel with energy monitoring. This allows improving the accuracy of predictions while simultaneously minimizing the instrumentation cost. On the other hand, real-time monitoring opens up the potential for smart operations [14]. Instrumentation costs make more financial sense, if the instrumentation cost can be justified with such benefits in addition to the performance prediction.

Incomplete Data and Uncertainties

Lack of post-retrofit performance data and cost data related to existing and novel retrofit options is a challenge for developing comprehensive retrofit plans and predicting EPC performance [21]. The said impacts reduce the investor confidence, community penetration potential of energy retrofits, and limit the creativity and innovation in energy retrofit projects [20]. Locally applicable databases containing energy savings and cost data, including capital and operational costs, can greatly support successfully planning retrofits projects. Building Performance Database in the United States is a great example of such database [28].

Lack of occupant awareness and operational condition variations can result in poor energy performance of buildings [23]. The “soft landing approach” was originally proposed for energy efficiency projects in larger buildings to enhance the occupant awareness about new technologies implemented in the buildings [18]. The same approach can benefit in enhancing the awareness of residential building occupants regarding energy conservation practices, thus reduce the contribution of human behavior towards design-performance gap. However, [29]. The operational uncertainties resulting from incomplete data and environmental conditions such as outside temperature and humidity cannot be controlled. Therefore, mathematical techniques can be used for uncertainty handling in the planning stages.

Epistemic and aleatory uncertainties heighten the design-performance gap. Previous studies on energy planning have used techniques such as Monte Carlo simulations, fuzzy logic, Robust Optimization, Taguchi Orthogonal Array, and Grey Numbers to handle these uncertain conditions [29,30]. Monte Carlo simulations attempt to model the probability distributions of the uncertain parameters and thereby predict the overall uncertainties associated with the outcomes [29,31]. On the other hand, techniques such as fuzzy sets [32] and Taguchi Orthogonal Array [29] attempt to approximate the potential uncertainties by employing three values to represent the uncertainty range and the likely value of input variables. Grey numbers have a similar approach, but it doesn't use the likely value and only use upper and lower boundaries to represent the parameter uncertainty [30]. Out of these models, Monte Carlo simulations have the ability to closely model the probability distributions of the output parameters as it uses actual probability distributions of the input variables [33]. Despite the accurate modelling of uncertain outcomes, Monte Carlo

approach has practical difficulty in handling higher number of uncertain parameters due to high computational power requirements and longer modelling times [29]. As the number of uncertain parameters were in a manageable range, Monte Carlo simulations were adopted in the proposed EPC planning model.

1.2. Business Models

Donal Brown has reviewed the opportunities and challenges associated with different business models in promoting residential retrofits in the United Kingdom [16]. Donal identifies five main business models commonly used in Europe, including the “Atomized” market model, market intermediation model, one-stop-shop, energy services agreement (ESA), managed energy services agreement (MESA). In the “Atomized” market model, the building owner deals with different suppliers, energy auditors, and financial bodies to make the retrofitting process a success. However, this approach does not facilitate a pathway for educated planning for a comprehensive retrofit strategy to achieve the expected energy and emissions savings, as highlighted by Donal. Moreover, it is mentioned that recruiting individual contractors who are not going to assume responsibility for the resultant energy and cost savings tends to deliver subpar outcomes and quality of workmanship [16].

In the market intermediation model discussed by Donal Brown, singular retrofits are being prescribed following a basic energy audit. Trustworthy intermediary partners such as local governments, government institutions, or major private sector players promote the retrofitting work and intervene in the project management work by means of supplying expertise and incentives [16]. This has a lot of similarities to the current state in BC, Canada. Local municipalities, governmental bodies such as CleanBC, and utility providers such as FortisBC and BC Hydro are working on increasing the community acceptance of retrofits via awareness programs and incentive schemes [5]. These initiatives have increased the motivation in the local communities to implement energy efficiency retrofits. However, this approach does not promote comprehensive retrofit planning, thus end up adding individual retrofits to the buildings. Moreover, the continuity of the retrofitting initiatives started by these programs heavily dependent on the incentives and backing provided by these agencies, which are heavily dependent on government policies [16] and the national economy. Promoting intermediary agencies such as ESCOs can support in overcoming this challenge as they are motivated to promote energy efficiency and high-quality project outcomes as that is a major part of their business model and profit-making strategy.

One-stop-shop (OSH), ESA, and MESA models discussed by Donal Brown can be mapped into different EPC approaches followed by the ESCOs in other countries. OSH approach includes a project management company that completes the required retrofitting requirement by dealing with one contractor or a reputable and closely connected group of sub-contractors [6,16]. An approach with a significant amount of similarities with the OSH was discussed in another study under the name “Energy Expense Entrusted” [13].

OSH approach may create higher pricing pressure for small-scale subcontractors in contrast to working with the building owner directly. Moreover, small-scale subcontractors may not always be the first choices of the ESCOs. This may create potential threats to small-scale local businesses [6]. However, on a positive note, the marketing done by the ESCOs for energy upgrades can create new retrofit project opportunities that can benefit many companies at the same time. One main advantage of this approach is the improved communication between the contractors [16]. This addresses the common issues in retrofit planning, such as oversizing issues, inefficiencies in retrofit investments caused by neglected interactions of energy system components, meeting the close tolerances determining the profitability and the quality of the outcome [10,13,17]. The ESCO and the Owner are closely tied into a financial commitment in an EPC. Both parties benefit from the energy and cost savings resulting from the renovation project in both financial models, including first-out and split energy savings [22]. The OSH is commonly discussed in other studies as well [13]. Due to the profit-sharing mechanisms involved, EPCs ensure the best possible quality of the project outcomes compared to a regular renovation project. In ESA, the ESCO guarantees a

minimum performance level such as a minimum heating temperature, a monthly volume of hot water supply, and total energy supply for a pre-defined period [6,17]. If unable to meet the promised performance level during the guarantee period, ESCO is liable for pre-defined service penalties [16]. This method can enhance investor confidence in retrofitting projects. MESA approach provides a complete energy management solution by assuming the responsibility of paying the energy bills and maintenance work on top of the ESA. This approach allows the ESCO to attempt aggressive strategies such as net-zero retrofitting with inhouse renewable energy generation if long contractual periods such as 30 years are involved [14,16]. Models with similar characteristics to MESA were discussed under the names “Chauffage” and “Chaffee”, in literature [14,32]. Capital investments for the latter three business models could be fully covered by the building owner (owner equity or third-party finance body) [14], ESCO (company equity), or a third-party finance body [6,16]. On the other hand, it can come as a split investment between the Owner and the ESCO or another financial institute [22]. Kupchik et al. and Carlo et al. discussed the financial implications of retrofit projects in reference to the outlay from the building owner and the equity from the ESCO. Moreover, impacts of the operational cost savings split between the Owner and the ESCO on the investment decision were previously investigated [14,21,32]. Assigning a higher share from the cost savings split to the ESCO can significantly reduce ESCO’s payback period and, therefore, the contract length of the EPC. However, if the financial benefit for the client is not significant, the project may not take place [21]. Therefore, determining the split of cost savings is a delicate matter. The current EPC planning models proposed in the literature is discussed in the following section.

1.3. Project Evaluation

Economic feasibility is a key determinant of the successful implementation of energy retrofit projects, thus the EPCs. Few approaches have been proposed for planning EPCs. Toppel et al. proposed a method to assess the risk mitigation potential of energy efficiency insurances and EPCs. This model considered stochastic uncertainties in natural, financial, and technological parameters [13]. Kullapa et al. proposed a Monte Carlo simulation-based approach for developing EPCs for residential energy retrofits. This study highlights the lack of information about the distributions of the uncertain parameters as a challenge for Monte Carlo approach [21]. Carlo et al. proposed a comprehensive financial performance assessment tool to evaluate the effectiveness of investments on an energy performance intervention from the building owners’ and ESCO’s views. This study evaluates first-out and shared saving models for EPCs. Moreover, it investigates the impact of different incentive schemes on EPC performance [22]. However, in this study, no emphasis was given to potential uncertainties associated with energy prices, behavioral variations, etc. Moreover, it focuses on finding the range of outlay from the building owner that produces mutual benefits to both parties. However, it does not focus on finding an optimum outlay from the building owners’ perspective. Kristaps et al. compare the performance of three financial models for building renovations in reference to three actual multi-unit residential buildings in Latvia. The case study results show that EPCs stand out against the other two approaches, including loan financed retrofitting without involving an ESCO and doing no renovation [34]. This type of practical example is essential to develop the confidence of the building owners and investors in EPCs. However, the said study does not propose an EPC planning approach. All the studies discussed above, overlooks the impact of the variations in the cost of capital and funding mechanisms involved on the financial performance of EPCs.

1.4. Research Gap and Contributions

Findings from the literature review indicated that a comprehensive investment evaluation model accounting for investment uncertainties and opportunity costs of investments for the multiple stakeholders involved was not developed. Moreover, the possibility of securing third-party loans and associated cost-of-capital variations were not modeled in

the previous studies. Therefore, this study focused on developing a model to identify the best EPC financial parameters for a given contract period. A non-linear optimization algorithm was developed to determine the optimal capital cost contributions and cost-saving splits among the stakeholders for different contract periods while accounting for uncertainties and varying decision priorities. Monte Carlo simulations were conducted to understand the impact of uncertainties on the optimal values and overall profits realized by the stakeholders involved. Energy simulations were employed to understand the operational uncertainties. Compared to data-driven approaches, the proposed energy simulation-based approach has greater adaptability for buildings located at different locations irrespective of the operational and the location-specific conditions. Key contributions of the proposed EPC formulation approach are summarized below:

- Proposing an energy performance contract planning approach for small residential buildings.
- Considering the impact of financial parameters on the “cost of capital” of the performance contract.
- Accounting for multi-stakeholder perspectives and uncertainties in the performance contract formulation process.
- Proposing an energy simulation-based approach for EPC planning under uncertain conditions.
- Developing a non-linear optimization algorithm for identifying the suitable profit splits and the optimal capital contributions for different contract periods.

The proposed EPC planning approach was demonstrated using a medium two-story single family detached residential building located in Kelowna, British Columbia, Canada as a case study. The specific details of the case study are presented in the Section 2.4.

2. Materials and Methods

The proposed optimization process for EPC-based retrofitting project planning involves five main steps, including retrofit options identification, energy performance simulation, key performance indicator identification, and EPC modeling. Retrofit options scenario prioritization has been comprehensively discussed in previous studies [10,32]. Therefore, this paper focused on the other main steps of retrofit project delivery. Overall decision-making process of the proposed EPC planning approach is summarized in Figure 1.

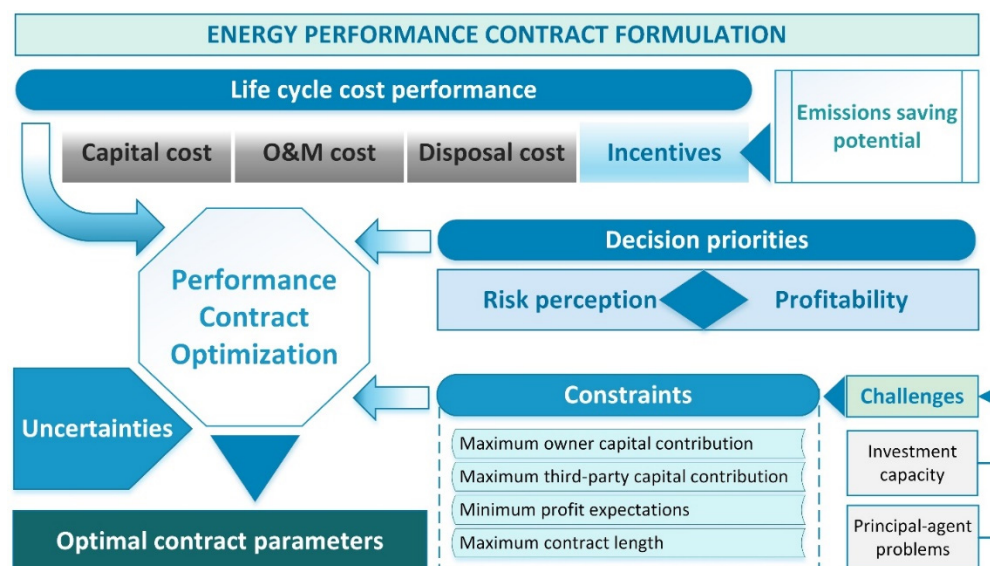


Figure 1. Overview of the proposed EPC planning methodology.

The detailed methodology followed in completing the said steps is presented below.

2.1. Energy Performance Simulation

HOT2000 (Version 11.3) was employed to simulate the energy performance of the selected case study building as it is the recommended and most commonly used energy simulation software package in the small residential building sector in Canada [6,29]. The Housing Technology Assessment Platform (HTAP) developed by Natural Resources Canada (NRCan) was employed to feed alternative retrofit strategies (combinations of different retrofit options) into HOT2000 [35]. Energy performance results from the simulations were combined with the emissions and cost factors in the later stages of the study to evaluate the economic and environmental performance of different retrofit strategies. Building energy performance is sensitive to building operational conditions such as heating setpoint, cooling setpoint, etc. [5,10]. Therefore, the energy performance uncertainties were simulated considering potential operational condition variations, as described in the Case Study section.

2.2. Key Performance Indicator Identification

Life cycle cost (LCC) and net present value (NPV), internal rate of return (IRR), payback period (PBP), and marginal abatement cost (The cost of avoided unit of pollution) (MAC) were used in literature to evaluate the financial performance of retrofit and EPC projects [6,21,31]. Life cycle cost is the net present value of all the cash flows involved during the life cycle of a given project. This assists decision-makers in understanding the overall financial performance of a project by the end of its life cycle. IRR is the discount rate at which the NPV of the project becomes zero. IRR is commonly compared against the weighted average cost of capital (WACC) to determine the profitability of a project. A higher IRR than the WACC usually indicates a good investment opportunity. The difference between IRR and WACC translates into the profit or the value addition created by a given investment to the investors [36]. Therefore, the WACC of a retrofit project can be used to understand whether that investment is financially feasible. The need of using WACC to understand the impact of using different financial sources (i.e., loans, owner equity, ESCO equity) is overlooked in the literature related to the EPCs. In this study, the life cycle cost savings (LCCS) for the Owner and the ESCO were considered as the performance indicators. WACC was used as the discount factor to accurately quantify the impacts of funding source on the project profitability.

2.2.1. Weighted Average Cost of Capital

The Owner contributes a portion of the initial capital from available funds to him/her. It was assumed that the ESCO leverages loans from third-party financial bodies to cover the balance of the initial investment when the Owner cannot or does not want to fully fund the project. In such a situation, the WACC of a project can be calculated using Equation (1).

$$r = \frac{IC_o * r_e + (IC - IC_o) * (1 - r_t) * r_d}{IC} = (1 - r_t)r_d + \frac{IC_o}{IC}(r_e - (1 - r_t)r_d) = \beta_1 + \beta_2 \frac{IC_o}{IC} \quad (1)$$

where,

- r —Weighted average cost of capital
- IC —Total initial capital requirement of the retrofit project
- IC_o —Capital investment from owner
- r_e —Cost of equity
- r_d —Debt Rate
- r_t —Tax Rate

WACC was used to discount the future cash flows of the retrofitting project. Depending on the financial constraints of the owner and/or the cost of equity, the project can either be financed solely by the owner or as a mix of owner equity and a loan.

2.2.2. Third-Party Financing

When the ESCO involves a third-party financing body, the loan installment can be calculated using Equation (2), assuming that the loan continues throughout the contract period.

$$LI = (IC - IC_o) * \frac{rd(T_C)}{1 - (1 + rd(T_C))^{-T_C}} \quad (2)$$

$rd(T_C)$ —Debt rate for the given contract period.

2.2.3. Life Cycle Profits Realized by the ESCO

For a given contract period (T_C), the LCCS realized by the ESCO was calculated using Equation (3).

$$f_1(x) = (ACS - k - LI) * \left\{ \frac{(1 + r)^{T_C} - 1}{r \cdot (1 + r)^{T_C}} \right\} \quad (3)$$

where,

k —Guaranteed cost savings to the owner

LI —Loan installment

ACS —Annual cost savings

T_C —Contract period

LI —Loan installment

The Life Cycle Profits Realized by the Owner

The LCCS realized by the building owner during was calculated using Equation (4).

$$f_2(x) = -IC_o + k * \sum_{t=1}^{T_C} \left\{ \frac{1}{(1 + r)^t} \right\} + ACS * \sum_{t=T_C+1}^{T_P} \left\{ \frac{1}{(1 + r)^t} \right\} \quad (4)$$

where,

T_P —Project period.

The project period is the total time that the owner is planning to own the house. After the contract period, owner is going to receive the entire cost savings produced by the retrofitting project as the ESCO is moving out of the contract. Even though the retrofits implemented are going to generate savings after the project period until the end of the lifetime of the retrofit, neither the ESCO nor the owner is going to receive any direct benefits. Therefore, the cost savings incurred after the project period were not considered in the EPC evaluation process.

2.3. Energy Performance Contract Formulation

ESCO and building owners compete with each other for profits after determining the costs of a given retrofit project. The ESCO help in increasing the confidence of the building owner to commit to a retrofit project by sharing the risk through an energy performance contract. The ESCO has to build a compelling argument in order to secure the project while maximizing their profits.

Generally, residential building owners have constraints on their maximum capital contribution. In such situations, the ESCO can cover the capital cost deficit by securing a loan by a third-party financial body. EPCs employ two main financial models, including the energy/cost savings guarantee and profit-sharing [13]. This paper employs the energy/cost savings guarantee model to demonstrate the proposed EPC formulation process.

2.3.1. Optimization Problem

The optimal values for the guaranteed cost savings to the owner (k) and capital investment from owner (IC_o) vary depending on the priorities assigned to the optimization goals, the capital contribution from the Owner, contract period, and operational uncertainties.

Therefore, an optimization algorithm was developed to find the optimal values for k and IC_o for a given contract period accounting for stakeholder decision priorities. The Monte Carlo approach was employed to account for uncertainties. The optimization variables can be presented by the following vector:

$$x = (IC_o, k)$$

The optimization was iteratively conducted for each contract period (T_C). For each $T_C = 1, 2, \dots, T_P$, the objective function $G(x)$ can be written as below:

$$G(x) = W_1 * f_1(x) + W_2 * f_2(x) \quad (5)$$

where,

W_1 —Weight of maximizing profits for the ESCO

$f_1(x)$ —Profits realized by the ESCO

W_2 —Weight of maximizing profits for the owner

$f_2(x)$ —Profits realized by the owner

The optimization has to be conducted binding to the constraints discussed below. The building owner should at least be able to provide sufficient initial capital to close the gap between the total capital requirement and the maximum capital contribution provided by the ESCO ($IC_{ESCO, Max}$) via third-party loans. Therefore, the following inequality must be satisfied.

$$IC - IC_{ESCO, Max} \leq IC_o \leq IC_{OWNER, Max} \quad (6)$$

Total profits realized by the ESCO has to be higher than or equal to their minimum profit expectation (η_1). Total profits realized by the Owner has to be higher than or equal to their minimum profit expectation (η_2).

$$\begin{aligned} \eta_1 &< f_1(x) \\ \eta_2 &< f_2(x) \end{aligned} \quad (7)$$

As the contract period increases, the ESCO has to keep on monitoring the project, and they increase the risk of facing cost-saving reductions due to component deterioration. Therefore, for each year the ESCO is in contract, there should be a compelling profit increment to compensate for the assumed risk. Thus, the minimum profit expectation of the ESCO was defined as a function of the contract period.

$$\eta_1 = \theta_1 + \theta_2 * T_C \quad (8)$$

where,

θ_1 —Starting profit level in order to enter the performance contract

θ_2 —Additional profit share per each year the performance contract continues

Following inequality must be satisfied for the project to be profitable.

$$IRR > WACC \quad (9)$$

2.3.2. Monte Carlo Simulations

A Monte Carlo simulation was conducted to investigate the associated uncertainties. Annual energy savings and energy prices were modeled as random variables that vary within a given range. The range was determined based on the operational energy saving variations obtained from the energy simulations and the energy price variations predicted based on potential future scenarios. The details of the simulation process and the energy price variations particular to the case study are discussed in the next section.

2.4. Case Study

The proposed research methodology was demonstrated using a case study as discussed below.

2.4.1. Base Building Characteristics

For demonstration purposes a two-story medium single family detached house located in Kelowna, BC, was chosen as the base building (BB). The volume of the house is 31,751 ft³ and the conditioned area is 1862 ft². Energy system and envelop characteristics of the base buildings were adopted from literature [5]. The base building characteristics are summarized in Table 1.

Table 1. Base building characteristics.

Heating	Hot Water	Window	Wall	Ceiling	Infiltration	Ventilation
Electric Baseboard	Conventional Tank (Electric) (EF = 0.55)	Single Pane	R10	R10	7.5 ACH @50 Pa	28 L/s

The baseloads created by the major electrical appliances, minor electrical appliances, and lighting were 10.68 kWh/day, 0.29 kWh/day, and 2.6 kWh/day, respectively. Average exterior energy use was assumed to be negligible. Hot water consumption was taken as 247 L/day. It was assumed that the house is occupied by three people who stay at the house during 50% of the time.

The total energy requirement of BB was 56,767 kWh (all energy provided by electricity). Similarly, the energy performance of the base-building after applying different retrofit strategies was simulated.

2.4.2. Retrofit Strategies

Space heating system, hot water unit, and building envelop related retrofits are commonly used to improve the energy performance of existing buildings. The best-performing retrofit options from the literature were considered for this case study [5].

The retrofit options considered Table 2 were combined to produce 128 retrofit strategies for the reference building. The LCCS produced by all retrofits was evaluated considering a ten year project period. The most cost-effective retrofit strategy was selected based on LCC savings. The proposed EPC planning model was applied to the most cost-effective option.

Table 2. Retrofitting options summary.

Heating	Hot Water	Window	Wall	Ceiling	Infiltration
Multi-Split ASHP HSPF-9.9 COP-2.9 28 kBTU	Heat Pump system (EF = 1.90)	Double Pane Low-E Hard Coat Air Fill	R31	R40	5.0 ACH @50 Pa
Tier-1 ASHP					
Tier-2 ASHP					

2.4.3. Uncertain Conditions

The uncertainties associated with energy savings of each retrofit strategy were quantified by simulating the varying operational conditions. Following operational variabilities (shown in Table 3) from the literature were adopted to represent the associated uncertainties with this case study [5].

Table 3. Operational Uncertainties.

Parameter	Energy-Conscious User	Average User	Consumeristic User
Number of adults	avg. + 1	3 adults [10]	avg. − 1
Percentage time inside the house	60%	50% [10]	40%
Appliance, lighting, and other loads	90% of avg.	Conditions from Prabatha et al. [10]	110% of avg.
Domestic hot water consumption and temperature	197 L, 53 °C	247 L, 55 °C [10]	297 L, 57 °C
Daytime heating temperature	20 °C	21 °C [10]	22 °C
Nighttime heating temperature	17 °C	18 °C [10]	19 °C
Setback duration	9 h	8 h [10]	7 h

The average electricity price was considered to be 11.62 cents/kWh with a 10% price variability [5].

2.4.4. Economic Parameters

This section contains the economic parameters used in the case study. The risk-free rate and the tax rate for home renovation projects were taken as 2.04% and 5%, respectively. The cost of equity for green and renewable energy projects was found to be 5.6% from the literature [37]. The debt rate variation with time was derived based on a data set on Canadian building renovation loan rates from an online resource [38,39]. The following trendline equation was developed to reflect the variation of the loan rate with the contract period (or the period for which the loan was taken).

$$r_d = (2.3746 * \ln(T_C) + 0.1866) * 10^{-2} \quad (10)$$

2.4.5. Decision Priorities

The decision priorities have to be found based on the Owner's and the ESCO's expectations for maximizing priorities. For demonstration purposes of the proposed algorithm, the decision priorities were adopted from the literature [5]. In order to understand the impact of the decision priorities on the final results, the algorithm was re-executed by altering the decision priorities following the scenarios listed in Table 4.

Table 4. Decision priorities.

Scenarios	W ₁ (ESCO)	W ₂ (Owner)
ESCO Profit Maximisation Scenario	2.25	1
Owner Profit Maximisation Scenario	1	2.25

2.4.6. Optimization Constraints

Minimum profit expectation of the ESCO depends on the company agenda. For demonstration purposes, the minimum profit requirement of the ESCO for entering the EPC (θ_1) and the minimum net present profit for staying an additional year in the contract (θ_2) were taken as 1000 CAD and 500 CAD/year, respectively. In this analysis, the annual overhead costs for the ESCO were not included as data relating to that are not available. However, when data is available, the overhead costs can be included as an annual cash flow that has to be borne by the ESCO.

The minimum net present profit expectation of the Owner from the project was set as 1000 CAD assuming that the building owner does not bear any additional cost than the planned capital cost contribution. During the contract period, the Owner has assurance from the ESCO regarding the energy savings. However, longer contract periods mean that the Owner has to share the profits with the ESCO for a longer period.

3. Results and Discussion

This section analyzes the results generated during the case study.

3.1. Cost Optimal Retrofit Strategy

The cost-optimal retrofit strategy was selected by ranking the considered retrofit strategies using a fuzzy number ranking mechanism (min-max method) [5]. In this ranking process, the LCCS was considered as the performance indicator. The chosen retrofit options and the capital costs associated with each retrofit are presented in the Appendix A. It is important to note that in this scenario analysis, the potential of source switching was not considered as switching from electricity to NG is not promoted in the British Columbian climate change mitigation discussion. However, if the potential of source switching was considered, substantially higher cost savings can be obtained due to the low energy cost of NG compared to electricity in Canada (Table 5).

Table 5. Capital cost of cost optimal solution.

System	Option	Capital Cost (\$)
ACH @50	5 ACH @50 Pa	1103
Wall	R31	4059
Window	Do not upgrade	-
Ceiling	Do not upgrade	-
Space Heating	Multi-Split ASHP HSPF9.9 COP2.9 28 kBTU	3700
Hot water system	Electric Heat Pump operated hot water system	2399
Total cost		11,261

The energy and cost savings achieved by applying the cost-optimal retrofit strategy is presented in Table 6. Savings were calculated assuming the operational parameters do not significantly differ from the usual operational conditions when the retrofits are implemented. The variability for the operational conditions for both pre- and post-retrofit periods was modeled considering the conditions presented in Table 4. A $\pm 10\%$ price variability in electricity unit price was considered when calculating the annual cost savings.

Table 6. Energy performance under uncertain conditions.

	Lower Bound	Likely Value	Upper Bound
Base Building (kWh/year)	51,086	56,767	62,596
Retrofitted Building (kWh/year)	22,383	24,932	27,627
Energy Savings (kWh/year)	28,703	31,835	34,969
Annual cost savings (CAD/year)	3410	3820	4238

3.2. Energy Performance Contract

The Monte-Carlo simulation was conducted considering a normal distribution for the annual energy savings (mean = 3820, range = [3410, 4238]) and the unit energy price (mean = 11.62 cents/kWh, range = [10.458, 12.782]). Both parameters were considered to be normally distributed in the given range and were modeled by 10,000 data points. The optimization results obtained from the proposed model are presented below. In the optimization, it was assumed that the Owner is going to own the house for at least 10 years. If the Owner decides to keep the house for more than 10 years, then the selected retrofit strategy is going to keep generating cost savings until the end-of-life cycle of the selected

retrofits, which can be expected to be around 15–25 years. Therefore, if the Owner keeps the house for a longer period, then they can realize higher profits than the values discussed in the sections below.

3.2.1. Owner's Profit Maximization Scenario

The Owner's profit maximization scenario was defined to give higher priority to the Owner's profit by assigning a higher weight to the Owner's expectations over the ESCO (2.25:1), as discussed in Section 3.1. The optimal range of guaranteed energy savings level and the optimal capital cost born by the Owner for each contract period is presented in Figure 2.

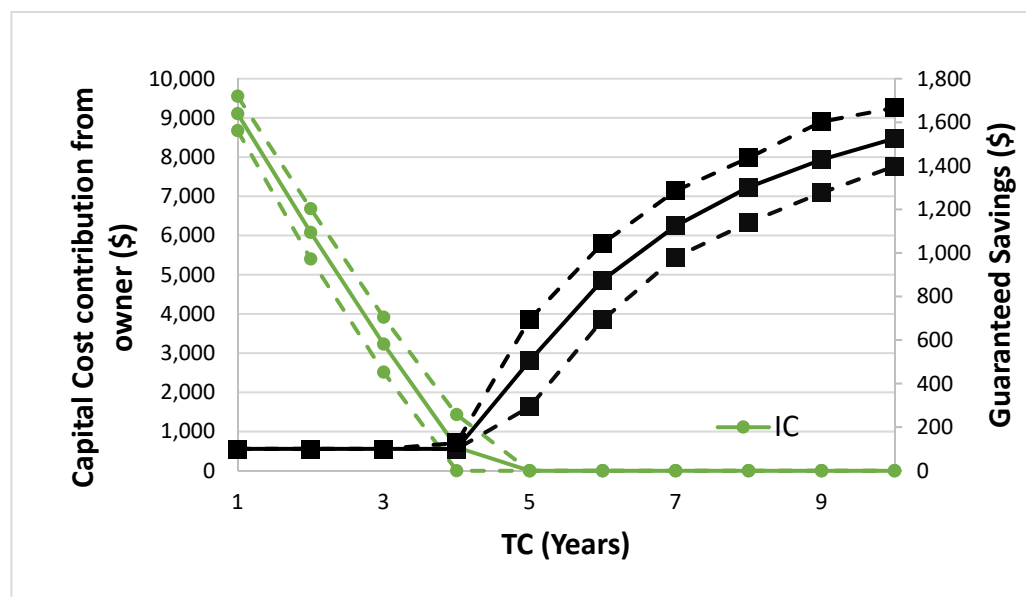


Figure 2. Owner's capital cost contribution and guaranteed savings against the contract period.

The dashed lines indicate the possible range of values that a given parameter can take due to uncertainties, while the solid lines indicate the likely scenario. This helps both stakeholders to understand the worst case, best case, and likely conditions to be expected from this contract. When the contract period is short, the ESCO has to secure a higher portion of the annual profits in order to achieve the expected minimum profit level. Therefore, the optimal guaranteed savings level stays at the minimum guaranteed cost savings value defined in the algorithm (100 CAD) up until the contract period exceeds 4 years. When the ESCO stays in the contract longer, ESCO realizes more profits compared to ending the contract in a shorter period. In that case, the owner capital cost contribution reduces, and the guaranteed savings amount increases in order to maximize the Owner's profit. Figure 3 presents the impact of the contract period and the optimization variables on the profits realized by the stakeholders.

According to Figure 3, until the contract period (T_C) reaches 3 years, the total project profit keeps increasing. However, after 3 years, the total project profit starts declining due to increasing WACC with decreasing owner capital contribution. This can be understood by paying attention to the constants β_1 and β_2 presented in Equation (1). Until $T_C = 3$, β_1 is higher than β_2 . Therefore, decreasing capital contribution from the owner help improve the total project profit by minimizing the WACC. However, when T_C exceeds 3, the debt rate keeps on increasing, causing the β_2 to be higher than β_1 , thereby increases the WACC causing a lower overall project profit. However, the Owner has to contribute a lower capital cost portion as their profit tends to drop with ESCO's demand of 500 CAD more from the net present profits for each year they stay in the contract.

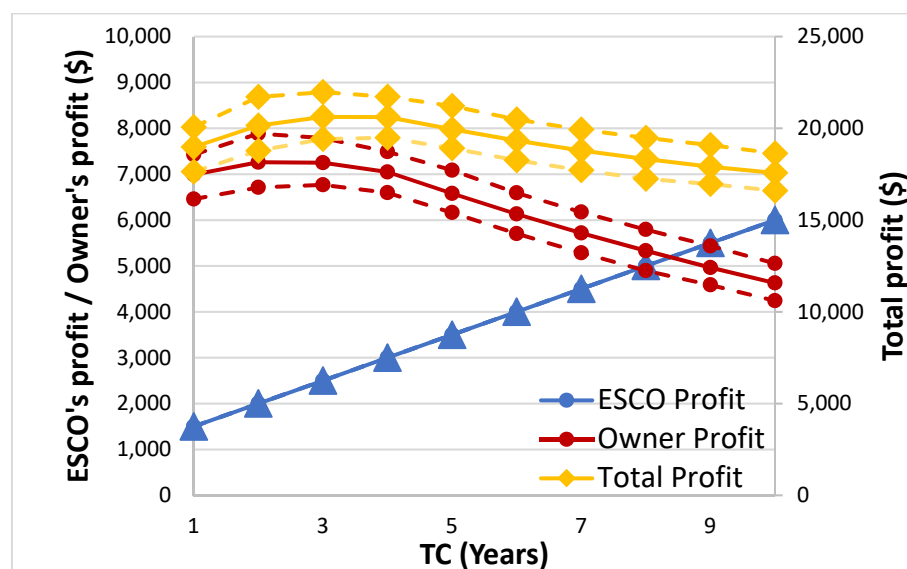


Figure 3. Owner's profit and ESCO's profit against the contract period (Owner's Profit Maximization Scenario).

Under the given decision priorities, it is beneficial for the ESCO to stay longer in the contract and maximize the profits. The Owner's profit maximizes if a contract period of 2 years is selected. However, it is important to note that when the ESCO moves out of the performance contract, there is no performance guarantee. Therefore, the Owner has to assume the risk of not receiving the promised savings if they want to maximize the profits. Even though longer contracts enhance ESCO's profits, the ESCO has to assume the risk of having to compensate for not being able to meet the promised energy savings by staying longer in the performance contract. Moreover, longer contract periods demand the ESCO to increase the debt portion of the initial investment, therefore, the company's liability. From the Owner's point of view, longer contract periods result in very low to zero capital contributions. This is beneficial for owners who are facing issues in securing the required capital cost for the project. Moreover, longer contract periods can help resolve principal-agent issues in rental properties when the ESCO is bearing the total capital cost. In such a situation, the ESCO can make their profit maximization a top priority. In conclusion, it is safe to mention that the contract period selection is a discussion that both parties must have at the contract formulation stage, considering their risk appetite and other conditions discussed above.

3.2.2. ESCO's Profit Maximization Scenario

This scenario was defined to give higher priority to ESCO's profit by assigning a higher weight to the ESCO's expectations over the Owner (2.25:1), as discussed in Section 2.4.5. The optimal range of guaranteed energy savings levels and the optimal capital cost born by the Owner for each contract period under given decision priorities are presented in Figure 4.

In this decision scenario, a higher priority was assigned to the profits realized by the ESCO compared to the owner. Therefore, the goal should be to get the maximum capital contribution from the owner while providing the minimum guaranteed savings during the contract period. At lower contract periods, maximizing the profits for the ESCO is harder due to the shorter time frame. Therefore, when the contract period (T_C) is shorter (≤ 5 years), the total capital cost is borne by the building owner, and only the minimum guaranteed cost-saving amount will be provided. As T_C gets closer to the project life, the capital cost contribution from the Owner decreases to enable realizing minimum profit expectations of the Owner. When the contract period is 10 years, the guaranteed savings slightly increase in order to meet the minimum profit expectations of the Owner.

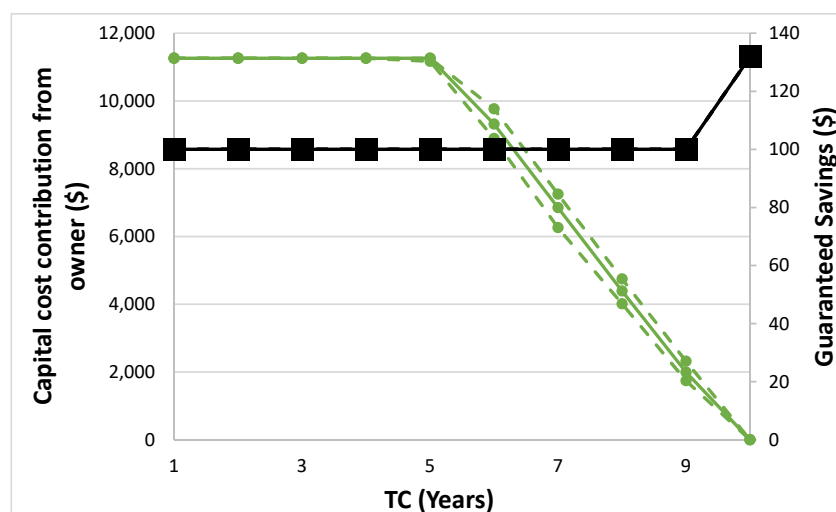


Figure 4. Owner's capital cost contribution & guaranteed savings against the contract period.

As shown in Figure 5, the profits realized by the owner decrease with the increasing contract period. If T_C extends beyond 5 years, the Owner can only realize the minimum profit expectation agreed before (set as a constraint in the contract formulation). On the other hand, the profits realized by the ESCO rapidly increase when T_C changes from 1 to 5 years. After, there is a gradual increase in the profit until $T_C = 7$. The slowdown of the profit increase and profit drop observed when T_C exceeds 7 years results from the increasing WACC due to increasing loan interest rates with the increasing contract period and the decreasing capital contribution from the Owner. Similar to the previous decision scenario, profits realized by the Owner are higher when the contract period is lower, while the ESCO can realize higher profits when the contract periods are longer. Moreover, the Owner may also like longer contract periods in rental situations as the capital cost requirement decreases. However, the same risks discussed in the previous decision scenario have to be borne by both parties when attempting to maximize profits.

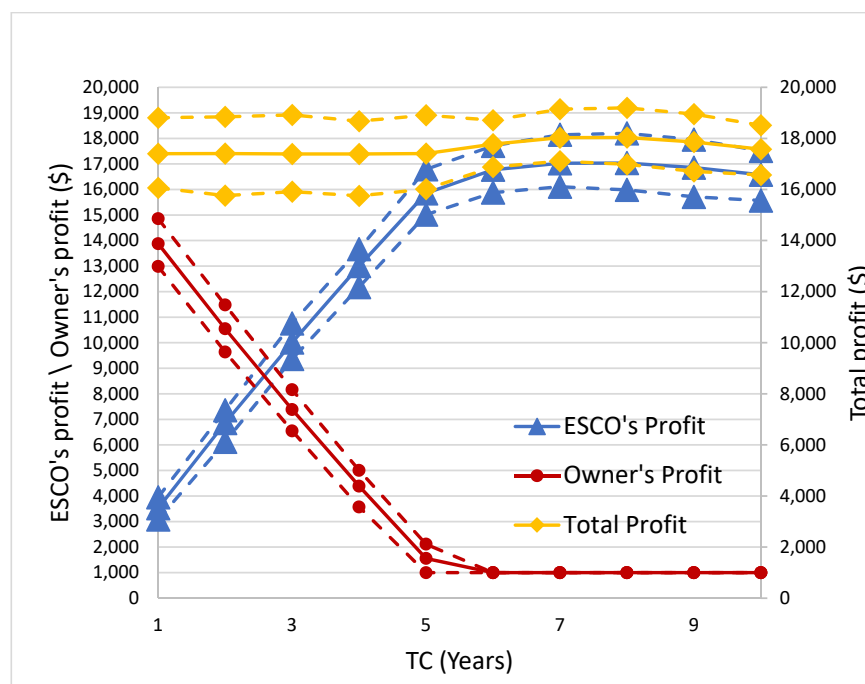


Figure 5. Owner's profit and ESCO's profit against the contract period (ESCO's Profit Maximization Scenario).

4. Conclusions

This paper proposed a novel energy simulation-based EPC formulation approach for residential building renovation projects. The proposed approach allows the decision-makers to select the contract parameters to match their risk appetite, and other priorities and constraints. Key conclusions derived from the study are discussed below.

- *Selected decision priorities can significantly alter the project outcomes*
The contract parameters were calculated considering two decision priority scenarios. The likely value of the overall project profit in the owner's profit maximization scenario varied between \$17,571 and \$20,626 with the changing contract period. The same for ESCO's profit maximization scenario varied between \$17,401 and \$18,035. This indicates that the decision priorities can significantly change the project outcomes and overall profits. Therefore, it can be concluded that the stakeholder priorities must be accurately understood before formulating an energy performance contract.
- *Contract period can significantly alter the stakeholder profit shares and risks*
According to the results, profits realized by the ESCO maximize with the increasing contract periods while the profits realized by the owner decrease as the contract period increases. However, longer contract periods reduce the risks faced by the owner of being affected by the design performance gap. On the other hand, extended contract periods increase the risk for the ESCO of having to compensate for the building owner if the upgrades fail to produce the anticipated savings. Therefore, both parties have to consider their appetite for risks and rewards when deciding on the contract period.
- *Financial capacity of the stakeholders must be considered when selecting the contract period*
In both decision scenarios, the owner's capital contribution changes with the changing contract periods to match the profit expectations of the stakeholders. Extended contract periods result in lower capital contribution from the building owner, binding the ESCO to higher loan amounts. Lower capital contribution requirements can help overcome capital cost barriers and uneven benefit distribution issues experienced by the owners in the (rental) housing market. Therefore, EPCs with extended contract periods can help to promote energy retrofits to the rental building sector overcoming the landlord-tenant dilemma.
- *WACC must be considered in EPC planning when more than one financial source is involved*
WACC has been overlooked in the previous EPC planning studies. However, variations in the owner capital contribution to loan ratio impact the weighted average cost of capital (WACC). The changes in the WACC result in \$3055 and \$634 variations in the likely overall profit of the project in owner's profit maximization and ESCO's profit maximization scenarios, respectively. This indicates the importance of employing WACC when evaluating the energy performance contracting projects with multiple funding sources.
- *Uncertainties can significantly alter the EPC outcomes*
The results showed that the uncertainties could change the optimal contract parameters and the expected profits significantly. For example, the overall profits realized in the owner's profit maximization scenario and ESCO's profit maximization scenario can vary up to 7.7% and 9.4%, respectively due to uncertainties. Therefore, uncertainties must be considered in the EPC planning stage.

In summary, EPCs can be employed to effectively deliver building energy retrofitting projects by overcoming common challenges such as capital investment barriers, lack of investor confidence, principal-agent problems such as landlord-tenant dilemma, and pre- and post-retrofit performance gap. However, the success of an EPC project depends on the economic performance of the implemented retrofits. Therefore, the retrofit strategy selection must be done carefully. On the other hand, the most cost-effective energy retrofit strategies may not necessarily provide environmental benefits. Therefore, policy tools such as guidelines, rebates, and incentives must be developed to simultaneously realize emission

savings parallel to cost savings from energy retrofitting projects. These policy implications need to be further investigated in future research.

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Nomenclature

ACS	Annual cost savings
ACH	Air changes per hour
BB	Base building
BC	British Columbia
BC-ESC	British Columbia Energy STEP Code
EEP	Eco-efficiency parameter
EF	Energy factor
EPC	Energy performance contracts
EPD	Environmental product declaration
ESA	Energy services agreement
ESCO	Energy service companies
GHG	Greenhouse gas
HDD	Heating degree days
HTAP	Housing Technology Assessment Platform
HP	Heat pump
HWU	Hot water unit
IC	Initial cost
IRR	Internal rate of return
LCC	Life cycle cost
MURB	Multi-unit residential buildings
MAC	Marginal abatement cost
MESA	Managed energy services agreement
NG	Natural gas
NRCan	Natural Resources Canada
NPV	Net present value
OSH	One-stop-shop
PBP	Payback period

Appendix A

Table A1. Capital costs and embodied emission data of the retrofit options considered in the study [5].

System	Option	Capital Cost
ACH @50 (Volume of the house: 31,751 ft ³)	5 ACH @50	1103
Wall (area: 2271 ft ²)	R31	4059
Window (area: 421 ft ²)	Double pane, Low-E High gain, Air Fill	24,448
Ceiling (area: 1114 ft ²)	R40	3944
Space Heating (Conditioned area: 1862 ft ²)	Tier1 Central Ducted ASHP	4620
	Tier2 Central Ducted ASHP	5020
	Multi Split ASHP HSPF 9.9 BTU/watt-hr COP 2.9 Capacity 28 kBTU	3700
DHWS	Electric HP	2399

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