Modeling and Analysis of Renewable Heat Integration into Non-Domestic Buildings - The Case of Biomass Boilers: A Whole Life Asset-Supply Chain Management Approach

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Abstract – This study proposes a whole life asset-supply chain optimization model for integration of biomass boilers into non-domestic (non-residential) buildings, under a renewable heat incentive scheme in the UK. The proposed model aims at identifying the optimal energy generation capacities and schedules for biomass and backup boilers, along with the optimal levels of biomass ordering and storage. The sensitivity of these decisions are then analyzed subject to changes in source, types and pricing of biomass materials as well as the choice of technologies and their cost and operational performance criteria. The proposed model is validated by applying it to a case study scenario in the UK. The

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results indicate that a Renewable Heat Incentive scheme could incentivize the adoption of biomass boilers, with a 3 to 1 ratio for biomass and backup boilers' utilization. As such, the findings from this study will be useful for industry managers, tasked with the decision of which biomass boiler system to utilize, considering the support from RHI. On the other hand, it is shown that RHI does not provide an encouragement for efficiency when it comes to the choice of biomass technologies and fuels. This presents itself as a major implication for the success and sustainability of the UK government's renewable heat incentive scheme.

Keywords: Renewable Heat Incentive; Biomass Boilers; Non-domestic Buildings; System Dynamics; Supply Chain Management; Asset Management

1. Introduction

Energy from renewable sources not only plays a critical role in cutting carbon emissions, but also reduces dependency on fossil fuels, promoting energy security. Increasing the share of renewable energy is a major component of many national and regional energy directives across the globe, such as feed-in-tariff and renewable portfolio standard policies, which are mostly directed towards creating a surge in renewable electricity generation capacities [1]. Globally, however, heating is associated with about half of the final energy use, compared to about 30% and 20% shares for electricity and transport [2, 3]. This clearly highlights the importance and impact of increasing the share of renewable energy sources for heat generation. Further, it should be mentioned that space heating and hot water in domestic (residential) and non-domestic (non-residential) buildings account for over half of the global energy needs for heating purposes [2, 3].

This study is based in the UK and it develops and presents a model that is applicable to making optimized decisions regarding the choice of 'building-integrated' biomass boilers under the renewable heat incentive scheme of the UK government. In the UK, when it comes to use of renewable sources, electricity generation accounts for 75% of all installed renewable energy capacities, followed by heat and transport with a share of 15% and 10% [4]. This lack of investment in use of renewable energy for heat generation runs contrary to the fact that heating accounts for over 40% of energy consumption in the UK [5]. In the particular case of non-domestic buildings, about half of the energy consumption is attributable to heating [6]. Based on this realization, integration of renewable heat technologies into non-domestic buildings has become an integral part of the UK Government's agenda for the building sector through the introduction of Renewable Heat Incentive (RHI) program in 2011 [7]. It is the world's first support program that directly pays and incentivizes the non-domestic building participants generating and using renewable energy (from certain eligible technologies) to heat their buildings [8].

For managers who wish to participate in this scheme and take advantage of the incentives from the government, there are several important decisions to be made regarding, for example, the capacity of the biomass boiler and the type of biomass boiler. It is important that the right combination of decisions is made in order to maximize the incentives received to avoid a loss-making investment. It is also important for the success and sustainability of the UK government's policy that a win-win scenario is generated such that the buildings that invest in biomass boilers are not financially disadvantaged. Being a pioneering scheme, there is currently no model that can be applied to support and direct the integration of biomass boilers in buildings under RHI.

Recognizing such a gap, in the following sections, we first present a literature review, then turn to a methodology section exploring the rationale behind developing our proposed model, its elements including the objective function, decision variables, and constraints. We further elaborate on the adopted optimization framework, followed by a case study and results analysis to implement the model, interpret the findings and report on sensitivity of a number of targeted parameters. The paper concludes with a research summary as well as recommendations for future research.

2. Literature Review

RHI is designed to bridge the gap between the cost of fossil fuel heat and that of renewable heat technologies, thus, encouraging private investments in decentralized heating [9]. In addition to carbon saving benefits, decentralized heat generation in cities from renewable sources (instead of heating from centrally supplied electricity or natural gas) helps reduce the pressure on urban energy supply infrastructure [10], increasing their resilience, longevity and reliability. Under the RHI scheme, the eligible technologies are solar thermal collectors, biomass boilers, ground-source and air-to-water heat pumps, and biogas waste digesters [7]. The amount of the incentive is calculated based on three criteria of “type of technology”, “generation capacity”, and “actual renewable energy use”. Table 1 presents the renewable heat incentive structure for non-domestic applications. The leading technologies are solar thermal and biomass boilers that could receive an incentive up to 9.2 and 8.6 pence per each KWh of renewable heat energy generated, respectively [7, 11]. The incentive payments are spread over 20 years and paid on a quarterly basis.

Biomass is the most utilized type of renewable energy in the UK that comprises a 70.7% share of renewable energy uses for electricity and heat generation (followed by wind at 20.8% and solar at 5.4%) [4]. It has a 2.3% share in electricity generation and 1% in heat generation [5]. The UK Bioenergy Strategy for 2020 targets an increase of biomass share to 5–11% in power generation and 6% in heating [12]. As a result, some researchers have investigated the factors that could influence the growth of biomass energy sector for heating and power in the UK [13, 14]. Biomass, in this context, refers to solid biomaterials (in form of woodchips, pellets, etc.) produced from agricultural residues, waste wood, and municipal solid waste.

With support from the scheme RHI, the installation and use of biomass boilers is becoming a leading choice (for renewable heating) in non-domestic buildings in the UK [15]. There are many reasons to back such a transition. First, RHI provides a high level of support for small scale (less than 200KW) biomass boilers, second only to solar energy [7]. Also, the levelized capital cost (cost per KWh) of biomass boilers is considerably lower that solar thermal collectors [8]. Moreover, the energy conversion performance of biomass boilers (KWh output per unit cost) is higher than alternative renewable heating technologies [15]. In addition, there exists a higher level of standardization in manufacturing of biomass boilers, while the alternative technologies are project-based with high dependency on characteristics of each specific site. This also creates the advantage of flexibility in terms of generation capacity when it comes to biomass boilers.

Last but not the least is the fact that biomass is a fuel-based source of energy with benefits for various stakeholders across its supply chain, contributing to its promotion [16]. The promise of biomass applies to society at large by reducing dependence on fossil fuels and transferring some of the weight to more sustainable and environmentally friendly biomass fuels. There are also implications for the reduction of fossil fuel distribution through expensive centralized piping systems. These are in addition to the commercial advantages to the supply chain partners including biomass fuel suppliers, boiler manufacturers and transportation companies.

Investigating and understanding the potentials and challenges of mass utilization of building-integrated small size biomass boilers for space heating and hot water is an emerging area. Kranzl et al. [19] have developed a simulation model to forecast the 2030 fuel-mix for space heating purposes in the EU countries, taking into account future scenarios of demand for space heating, potentials for renewable support policies and incentives, and expected energy (and fuels) prices. They have identified the integration of "small-scale biomass boilers" as one of the core drivers for future growth in renewable heating. Saidur et al. [20] provided a review of biomass boilers including common technologies, suitable fuels, and their advantages and disadvantages with respect to cost, requirements, operational performance and environmental impacts. As a result of the potential advantages of economies of scale [21], supplying renewable heat to buildings through utilization of biomass boilers for district heating is also receiving growing attention [22, 23]. McManus [24] has provided an environmental assessment framework to quantify the emission levels from a number of case study small size biomass boilers in the UK. Numerical models and computer simulations were also suggested to monitor and control the operation of small size biomass boilers with the aim of increasing the energy efficiency and/or reducing NOx and CO emissions [25, 26]. Further, operational performance optimization frameworks were proposed to identify the optimal of mix of biomass fuels [27] and the optimal size of thermal storage for biomass boilers [28].

As the promotion of renewable heat technologies under the RHI scheme is a recent phenomenon, there has been very little research reported on the supply chain and asset management performance of the building-integrated biomass boilers (from cost, reliability, and environmental perspectives) with the existence of such an incentive [15, 29].

Despite the recognized advantages of installing localized biomass boilers, there are also inherent risk factors. If not properly installed, the indoor air quality may deteriorate due to NOx, CO and other air pollutants from biomass burning [30, 31]. Biomass boilers operate with a lower energy conversion performance compared to natural gas boilers, requiring a considerable space for biomass storage. More importantly, as biomass is a seasonal (and mostly foreign) source of fuel, it requires a back-up natural gas boiler, presenting some challenges with respect to the need to a dual capacity planning (for two boilers) and availability of space (for both boilers and storage). The relaxation of energy consumption targets is another cause for concern. The concern is that by installing biomass boilers, building/facility managers can achieve the carbon target without making any extra efforts on energy conservation [5]. Thus there is a concern that behavioral patterns that develop may not be fully aligned with what was desired.

There are also variations in type, quality and supply chain characteristics of biomass materials with direct impact on their logistics and storage [32, 34], as well as indirect influence on cost, energy efficiency, carbon performance, and operational requirements of boilers [17, 18]. This is an important factor when considering the success of the RHI scheme as it should be able to promote the use of more efficient and sustainable biomass materials [5, 13].

3. Problem Statement

This study is a first attempt to propose a whole life asset and supply chain simulation and optimization model to capture the integration of biomass boilers into non-domestic buildings with incorporation of back-up natural gas boilers. Figure 1 captures the elements of such a model with choices (decision variables) on suppliers, biomass purchase, boilers' capacities and their utilization subject to changes in biomass inventory levels and energy demand over time. Subject to various operational constraints including those on air pollution criteria, the model aims at identifying the optimal values of the above mentioned decision variables while minimizing the whole life cost of the system. A "whole life" perspective, as advocated in the asset management literature, is a costing scope that accounts for the ownership costs associated with physical assets during their service and residual life [35]. Through a case study, the sensitivity of the outcomes are then analyzed subject to changes in source, types and pricing of biomass materials as well as the choice of technologies and their cost and environmental performance profiles.

4. Methodology

Energy production from solid biomass comes with a number of peculiar supply chain management issues. Those are the seasonality of biomass (and its supply), variations in types and quality of biomass materials, multiplicity of suppliers with varied characteristics, and environmental impacts of biomass transport [18, 33]. These issues can create complexities and uncertainties with respect to the use of biomass boilers. Consequently, there are important decisions to be made with respect to the installation and running of biomass boilers. In case of small biomass boilers (for domestic and non-domestic applications), there are further asset management challenges including the availability of various boiler technologies with varied capital intensity and operational performance, space requirements for the boiler, its backup, and biomass storage, and consideration of indoor air quality criteria [20].

In this sense, integration of biomass boilers into non-domestic buildings in the UK (as encouraged by RHI), needs to be carefully crafted using a combined supply chain/asset management model that addresses the above-mentioned issues. In such a model, we need to deal with decisions such as the selection of biomass sources, quantity and timing of orders, storage capacities, boilers' capacities, and energy production schedules. These decisions are made such that the system yields a minimum total cost that includes its supply chain expenditures as well as the capital and operational costs of its physical assets while meeting energy demand and certain technical and environmental constraints.

Several surveys of supply chain models with source selection, order allocation, and storage and production planning components have been reported in the literature [36, 37]. In case of bioenergy, Mafakheri and Nasiri [18] have reviewed decision support and optimization models that have been developed in line with various operations along the bioenergy supply chains including harvesting, storage, transport, and energy conversion. Considering the literature on biomass supply chain modeling, there is a clear gap in the models that can address the peculiar supply chain and operational attributes of "building-integrated" biomass boilers. Consequently, given the encouragement from non-domestic renewable heat incentive policy, and with respect to the supply chain and asset management peculiarities of biomass boilers, we propose a combined life supply chain-asset management model for integration of biomass boilers into non-domestic buildings in the UK. The proposed model identifies an optimal integration and operation plan, optimizing the total cost of biomass boiler's ownership over its service life, with decisions on biomass purchase, main and backup boilers' capacities, and their energy production levels that evolves over time. The model, with its objective function and the associated technical, operational, and environmental constraints, is presented through the following equations (descriptions of the symbols used in the model are provided in the nomenclature section at the end):

The objective is to minimize the whole life (including asset management and supply chain) cost of biomass and backup boilers over a targeted service life of *T*:

Minimize

$$\begin{aligned}\pi = {} & \overbrace{\sum_{t=1}^{T}\sum_{i=1}^{n} p_i^{(t)}.s_i^{(t)}}^{\text{Biomass Purchase}} + \overbrace{\sum_{i=1}^{n}[c_i.\sum_{t=1}^{T} s_i^{(t)}]}^{\text{Biomass Transport}} + \overbrace{h.\sum_{t=1}^{T} I^{(t)}}^{\text{Biomass Storage}} + \overbrace{\sum_{t=1}^{T} p_g{}^{(t)}.y^{(t)}}^{\text{Natural Gas Cost}} - \overbrace{\sum_{t=1}^{T} \beta^{(t)}.x^{(t)}}^{\text{RHI Benefit}} \\ & + \underbrace{c_b.\sum_{t=1}^{T} x^{(t)}}_{\text{Biomass Boiler Utilization}} + \underbrace{(v + c_g).\sum_{t=1}^{T} y^{(t)}}_{\text{Backup Boiler Utilization}}\end{aligned} \qquad (1)$$

Subject to the following constraints, and conditions:

$$I^{(t)} = (1-\alpha)I^{(t-1)} - \frac{1+\varepsilon}{r_b}x^{(t)} + \sum_{i=1}^{n} s_i^{(t-t_i)}\;; \tag{2}$$

Eq.2 captures the biomass inventory at the end of any period of time, which is equal to the amount of in-hand inventory, $I^{(t\text{-}1)}$, that deteriorates with a spoilage rate of α, minus biomass used in that period calculated based on converting biomass energy generation using biomass materials energy content (which is varying for different biomass materials) and boiler's efficiency rate (which is varying for different boiler technologies), and finally adding the biomass purchases that arrive for storage in the given period.

The above inventory level has a non-negative value (at least no inventory is in place) and is constrained by a maximum storage capacity due to space limitations:

$$0 \le I^{(t)} \le \bar{I}\;; \tag{3}$$

Also, the purchase from each supplier is a time dependent variable and could fluctuate over time due to changing needs of the client as well as the seasonality of biomass that impacts the capacity of suppliers:

$$s_i^{(t)} \le S_i\;; \tag{4}$$

There shall be a balance equation between heating energy generation and consumption from boilers:

$$x^{(t)} + y^{(t)} = D^{(t)}\;; \tag{5}$$

We assume a preferential pricing from the suppliers (i.e. higher purchase from a particular supplier leads to a discount):

$$p_i^{(t)} = P_i(1 - k_i \frac{s_i^{(t)}}{S_i}); \tag{6}$$

And more important, as per Table 1, the RHI mechanism links the amount of incentive to the hours of operation for the biomass boiler. In this sense, the RHI incentive rate is calculated based on the ratio of biomass energy generation to biomass boiler's capacity. This is where the non-linearity is introduced to our model:

$$\beta^{(t)} = \begin{cases} \beta_1 & \frac{1}{X}.\sum_{r=t-12}^{t} x^{(r)} \le H \\ \beta_2 & otherwise \end{cases}; \tag{7}$$

The generation of energy from biomass and natural gas is not only bounded by the boilers' capacities but also is subject to boilers' availability at any particular point of time (i.e. accounting for the times that the boilers are unavailable for periodical service and maintenance):

$$x^{(t)} \le w_b^{(t)} X; \tag{8}$$

$$y^{(t)} \le w_g^{(t)}.Y; \tag{9}$$

The decisions on boilers' capacities are subject to the availability of space. The size of boilers dictates the dimensions of the boiler room as it should host the boilers, their associated hot water thank(s), panels, pipes, as well as the adjacent storage space for biomass following certain benchmarks [15]:

$$l(X,Y) \le L; \tag{10}$$

There are standards for air pollution criteria as well as targets for carbon emissions that could influence the energy generation mix from biomass and backup boilers:

$$\sum_{t=1}^{T} e_j(x^{(t)}, y^{(t)}) \le E_j \quad (j=1, 2, \dots m); \tag{11}$$

$$\sum_{t=1}^{T} e(x^{(t)}, y^{(t)}) \ge E_0 \tag{12}$$

And finally, the non-negativity conditions on supply and generation decision variables as well as the biomass and backup capacity requirements:

$$s_i^{(t)},\ x^{(t)},\ y^{(t)} \ge 0 \text{ and } X, Y > 0 \tag{13}$$

The schedule of the above decision variables is identified by simulating and optimizing the above multi-period non-linear model over the targeted service life of the system. We adopt the use of a system dynamics (SD) approach. Research in the use of system dynamics modeling in supply chain management is established in academic literature [38], mostly in close loop supply chains [39, 40] and reverse logistics [41]. System dynamics (SD) is a modeling framework developed in the 1960s [42] for analyzing the behavior of complex systems that evolve over time. The SD approach is a well-suited framework for our proposed model as; (1) the objective function (total cost of boilers' ownership incorporated with the benefits from RHI), constraints (such as energy demand and biomass supply) and external drivers (such as energy prices and incentives) are varying over time, (2) there are a schedule of decisions made over time (capacities, production levels, and biomass purchase), (3) decisions made in one stage impact the ones in the subsequent stages, and (4) there are feed-back loops (circular causal relationships) in the model governing the interactions among various components of the model (as presented in Figure 2).

Figure 2 indicates that although heat energy generation from biomass boilers in non-domestic buildings is encouraged by the renewable heat incentive scheme, it is constrained by space requirements (eq. 10) as well as decisions on capacities (eqs. 8 and 9) and inventories (eqs. 2 and 3). Eq. 2 captures the balancing relationship between biomass energy generation, $x^{(t)}$, and inventory of biomass, $I^{(t)}$, in which an increase in the former leads to a decrease in the latter. Replacing $I^{(t)}$ with its equivalent from eq. 2 in the left side of eq. 3 (i.e. $I^{(t)} \geq 0$), we can depict the reinforcing relationship between biomass inventory, $I^{(t-1)}$, and biomass use for energy generation, $x^{(t)}$ (i.e. energy generation from biomass is bounded by the inventory already in place). These causal relationships form a balancing "asset management loop". On the other hand, the availability of biomass materials imposes a balancing "supply chain loop". First, eq. 2 shows the reinforcing (linear) relationship between the sum of biomass orders (purchases) from suppliers to arrive at time *t* and the expected level of biomass inventory, $I^{(t)}$ (i.e. for any given level of biomass energy generation, the more the purchase the higher the inventory). In addition, replacing $I^{(t)}$ with its equivalent from eq. 2 in the right side of eq. 3 (i.e. $I^{(t)} \leq \bar{I}$), for any given level of biomass energy generation, $x^{(t)}$, a higher level of expected in-hand biomass inventory, $I^{(t-1)}$, reduces the need to biomass ordering from suppliers for arrival at time *t*.

As per Figure 2, these asset management and supply chain balancing loops, constrains the continuity of biomass boilers' operation, resulting in higher cost and lower operational performance for such boilers. This phenomenon necessitates the existence of the renewable heat incentive as a driving force to compensate on the price of biomass, which incentivizes the purchase of biomass, resulting in higher biomass inventories, and thus an increased level of biomass energy production. It should be mentioned that each arrow in Figure 2 captures the relationship between its tail and head variables. A "+" sign indicates that an increase in the arrow tail variable could lead to an increase in the arrow head variable. A "-" sign means that an increase in the arrow tail variable could lead to a decrease in the arrow head variable.

With respect to the above balancing loops, the proposed model (eqs 1-12) is implemented in a SD simulation-optimization platform using Vensim modeling (professional edition 5.9e) software [43]. This model, as presented in Figure 3, is comprised of stock (boxes) and flow (double line arrows) elements, representing state and rate variables of the system, respectively. Consequently, biomass fuel inventories, the boiler's total cost of ownership, and total carbon savings are presented as stock, with their inflows and outflows as flow variables. The model is optimized with respect to the total cost of ownership, which is the cumulative sum of asset management and supply chain costs. When implemented in Vensim, we calculate the net present value of this cost to incorporate the impact of interest rate. The aim is to identify the optimal (i.e. least cost) levels of biomass purchase, utilization, and (biomass and backup) boilers' capacities (as presented in red color in Figure 3), with respect to scenario parameters as relate to source of biomass, pricing and type of biomass boiler (as presented in green color in Figure 3), in addition to other influencing parameters (a full description of the model's equations as implemented in Vensim platform is provided in the appendix). In the following section, we will simulate and optimize the model using Vensim's optimization toolbox [43] based on data from a case study. In doing so, we analyze the impact of a renewable heat incentive (for non-domestic renewable heat generation) on transition from a natural gas-only heating system to a biomass one (with a backup natural gas boiler) and the arising sensitivities subject to changes in source, types and pricing of biomass materials as well as the choice of technologies and their cost and operational performance.

5. Case study

Transition from a natural gas-only heating to a biomass one is sought for a local authority building in south London, UK. The aim is to benefit from the recently introduced Renewable Heat Incentive for non-domestic buildings while supporting local biomass suppliers as well as contributing to the local government's carbon mitigation agenda.

The building, comprised of a floor area of 20,000 m2, is currently served by a 500KW natural gas boiler. Due to seasonal variations, the energy demand for heating in this building fluctuates from approximately 5MWh in July to just over 20MWh in January. The size of the floor area and the amount of heating energy demand makes this building a representative case study for RHI implementation, benefiting from the economy of scale when integrating renewable energy technologies such as biomass boilers. The location of the building in London is also positioning it with easier access to local suppliers of biomass across the UK and in Europe.

It is envisioned that the current boiler is replaced with a biomass boiler in the capacity range of [300, 400] KW to be accompanied by a back-up (natural gas) boiler in range of [100, 200] KW. We did not consider any such boundaries on capacities in the proposed model. But in the case study, from a practical point of view, the client opted for these boundaries for several reasons. First, they wanted to make sure that the biomass boiler is the main boiler and the natural gas boiler will only be a backup one. Second, the company providing the biomass boiler is one of the very few that manufacture larger biomass boilers but is not manufacturing biomass boilers above 400KW due to lack of many customers for that range of capacity. Third, biomass boilers need more space compare to the natural gas one, for the boiler and biomass storage. Space limitation is a barrier for installation of larger biomass boilers in the case study building. The total available space for the boilers and storage would be 70m3 (considering a plant room height of 3.5m). Based on a recent study in London, there are two types of biomass fuels, , wood chips and wood pellets, which are competitive in terms of availability, price, physical density and energy content as presented in Table 2 [15].

Minimizing the total cost of the proposed system, which includes asset management and supply chain costs, according to eq. 1 and subject to eqs. 2-12, will result in making decisions on boilers' capacities, their operational plans, and biomass ordering quantities and timing. Figures 4-6 show the outcomes of the optimization process using a Vensim optimization platform [43] which utilizes a Powell hill climbing algorithm [44] to search for the optimal plan over a targeted service life of 25 years.

As energy demand in the building is varying on a monthly basis, for the sake of the clarity and simplicity of presentations, the results for the first 48 months are shown in Figures 4-6. Switching to a medium size biomass boiler in the capacity range of [300, 400] KW, according to Table 1, could yield an incentive of 0.05 GBP/KWh, if operated less than 1,314 annually, otherwise it is associated with an incentive of 0.021 GBP/KWh. Optimizing the model. On that basis, the installation of a 400KW biomass boiler, accompanied by a 100KW backup one, is recommended.

In this sense, we have the following outcomes as the long-run service life operational plans of the boilers: The cumulative annual utilization of biomass boiler is identified as reaching 306 hours annually (Figure 4a), which is associated with the higher bound of the incentive. Keeping the operational hours to such a level is made possible as a result of the use of an 8 m^3 buffer (hot water) tank (included in the biomass boiler's cost and space estimations). The backup boiler's operation, as shown by Figure 4a, is mainly happening during the peak demand period in winter. Once the system establishes a reliable level of biomass storage, the share of backup boiler further shrinks and we reach approximately a 3 to 1 ratio for (biomass and backup) boilers' utilization. The monthly utilization numbers ranges seasonally from 3,888 to 15,261 KWh for biomass boiler and from 912 to 4,464 KWh for the natural gas boiler. As depicted by Figure 5, until the system reaches a reliable system of inventory, there would be two peak orderings for biomass in each of the first two years, which will reduces to one occasion thereafter. In the long run, the orders will establish a seasonal range from 1.20 to 6.30 tons of biomass. The system will also maintain a safety inventory of 4.50 tons of biomass materials throughout its service life.

According to Figure 6, the renewable heat incentive will cover approximately a quarter of the costs associated with biomass boiler's utilization, enough to establish it as the main heat producing boiler in our least total cost solution. In the light of the above results, we now develop a sensitivity analysis to investigate the impact of source, types and pricing of biomass materials as well as the choice of technologies (efficiency versus cost) on the outcomes of the optimization, and in particular, the optimal production plan and total cost.

6. Results Analysis

When it comes to biomass boiler's technologies, their difference is in the types of biomass materials they can handle with respect to the moisture content and particle size. The potential for such variations was captured in the proposed model by introducing a "Boiler's Efficiency Coefficient", ranging from 0 to 1, where a higher value represent a more tolerant boiler. It is also the case that the boilers with higher tolerance would have a higher price tag. Figure 7 presents the range of values which correspond with various boilers' technologies and that match the required capacity [15], with differences that originate from their feeding mechanism, grating system, and combustion technology. On the other hand, the choice of biomass materials could also vary greatly. Again, Table 2 captures the range of values associated with such a choice. The pricey wood pellets have higher energy content and physical density, which means a better combustion and storage efficiency, compared to the cheaper woodchips. Figure 8 presents these variations based on the values shown in Table 2.

This study presents a sensitivity analysis using Vensim sensitivity analysis platform [43] to investigate the impact of variations in (1) the efficiency and price of biomass boiler's technology (Figure 7) and (2) the choice of biomass materials (Figure 8), on the main service life characteristics of the system, namely the extent of energy generation from biomass and the associated total cost. This analysis is subject to the key assumption that all other parameters of the model are fixed while varying the two indicated parameters.

Assuming that the above choices for technologies and materials are available for our case study, we consider that the variations follow a uniform distribution, giving each value the same likelihood. Figure 7 shows that when installing a more expensive biomass boiler (with a higher reliability and a better rate of biomass-to-heat conversion), the potential to use biomass in heat supply could be negatively impacted. This is due to the fact that the increase in capital costs (associated with the more efficient boiler technologies) will not fully be offset with the operational gains and support from Renewable Heat Incentive. Thus, for building managers, it will be more financially logical to favour higher dependence on the cheaper natural gas (back-up) boiler. On the contrary, switching to a more efficient fuel option (with a higher energy content and density) will not contribute to a considerable change in the share of biomass-based heat as the operational gains due to a better storage and conversion performance are offset by the higher biomass prices that contribute to an increase in the overall cost of the system. Thus while this option is somewhat more financially viable than the former option, it is not without its drawbacks.

These are important findings that show that even with the availability of support from a renewable heat incentive (RHI) scheme, there would be no motivation to go for a better performing biomass boiler technology or a more efficient biomass fuel option. This is mainly due to the fact the RHI scheme does not provide a prioritization based on the type of technologies or fuel options, it is only concerned about the size and extent of the utilization of the technology. The findings reconfirm the lack of encouragement for efficiency as a major issue when it comes to supporting mechanisms for renewable energy generation. This has major implications for the government's RHI scheme as it suggests that the scheme itself may not be surgical enough as it does not take into account, the specific impacts of technology type or biomass fuel characteristics.

7. Conclusion and Policy Implications

This study proposed a simulation-optimization model to capture the whole life asset and supply chain management elements of building-integrated biomass boilers. It paid particular attention to incorporate the recently proposed UK government's renewable heat incentive scheme for non-domestic buildings. The study validated the model by applying it to a real-world case study and analyzed the results of its applicability.

By considering a whole life costing approach, we created a model that incorporated the costs associated with supply, storage, and use of biomass as well as the capital and operational costs of biomass and natural gas boilers throughout their service life. In this sense, we were able to investigate the impact of RHI on the asset management and supply chain characteristics of building-integrated biomass boilers. From an asset management perspective, it identified the optimal energy (heat) generation capacities and schedules for biomass (and backup) boilers, linking them to supply chain-related decisions on levels of biomass source, ordering and storage. The sensitivity of those decisions, subject to variations in biomass boiler's technologies (considering their capital costs and operational performance) and biomass materials (considering source, types and pricing) were further analyzed.

The results indicated that, the availability of a Renewable Heat Incentive policy scheme was effective in incentivizing the switch to a biomass boiler but it did not encourage shifting to more efficient boiler technologies or biomass fuels. This is a common problem with the renewable energy support mechanisms that provide direct incentives (such as feed-in-tariff policy), as they encourage the uptake of more expensive renewable means of energy generation through a direct incentive without creating a motivation for more (cost and energy) efficient practices. In this sense, the adoption of (or mixing RHI with) a renewable portfolio standard (RPS) policy can be envisioned as a way to address the efficiency when encouraging building-integrated renewable heat technologies. An RPS sets targets for renewables but leaves the choice of technology and fuels to the developers, leading to adoption of more cost-efficient options in long term [1]. In contrary, RHI creates a quick surge towards the renewable technologies. The ideal picture would be a combination of such policies to create a compromise between effectiveness of RHI and efficiency of RPS policies.

This study could be extended in different ways. First, the model could be adopted for larger scale district heating systems with multiple users. It is possible that the economies of scale could result in different outcomes compared to the ones found in this study. In addition, future studies may consider a scenario where the value of the renewable heat incentive is determined endogenously. Such a study could indicate if there is an optimal level of support for our specific case study and if it is beneficial to provide RHI support on the basis of the characteristics of individual projects.

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Nomenclature

π : Whole life (ownership) cost for the main and backup boilers (GBP)

t : Time step (Month)

T : Targeted service life (Month)

n : Number of potential suppliers

$p_i^{(t)}$: Supplier ‘i’ price for biomass at period ‘t’ (GBP/kg)

$s_i^{(t)}$: Biomass supply from supplier ‘i’ at period ‘t’ (kg/Month) – Decision variable

c_i : Cost of biomass supply (including ordering and transport) from supplier ‘i’ (GBP/Month)

h : Holding cost of biomass (GBP/kg)

$I^{(t)}$: Biomass storage (buffer) at period ‘t’ (kg)

${p_g}^{(t)}$: Natural gas price at period ‘t’ (GBP/KWh)

$y^{(t)}$: Heating energy (production) from natural gas (backup) boiler at period ‘t’ (KWh/Month) – Decision variable

$\beta^{(t)}$: Rate of renewable heat incentive (RHI) at period 't' (GBP/KWh)

$x^{(t)}$: Heating energy (production) from biomass boiler at period 't' (KWh/Month) – Decision variable

c_b : Levelized (capital and operational) cost of biomass boiler (aggregated over its service life) (GBP/KWh)

v : Climate change levy (for energy from fossil fuels) (GBP/KWh)

c_g : Levelized (capital and operational) cost of natural gas (backup) boiler (aggregated over its service life) (GBP/KWh)

α : Biomass materials deterioration (spoilage) rate (1/Month)

ε : Biomass boiler's efficiency ratio (dimensionless)

r_b : Biomass materials' energy content rate (KWh/kg)

t_i : Supplier 'i' order (delivery) time (Month)

$\overline{I}$: Available storage capacity (Cubic Meter)

S_i : Supplier 'i' order capacity (kg/Month)

$D^{(t)}$: Building energy demand at period 't' (KWh/Month)

P_i : Supplier 'i' base price for biomass (GBP/kg)

k_i : Supplier 'i' discount ratio (dimensionless)

H : RHI's preferred target for biomass boilers' cumulative hours of operation (on a yearly basis) (Hour)

β_1 : Rate of renewable heat incentive (RHI) for boilers operating within the preferred target (on a yearly basis) (GBP/KWh)

β_2 : Rate of renewable heat incentive (RHI) for boilers operating beyond the preferred target (on a yearly basis) (GBP/KWh)

X : Biomass boiler's capacity (KW) – Decision variable

Y : Backup boiler's capacity (KW) – Decision variable

$w_b^{(t)}$: Availability of biomass boiler at period '*t*' (Hour)

$w_b^{(t)}$: Availability of backup boiler at period '*t*' (Hour)

$l(X,Y)$: Space requirement for biomass and backup boilers (including storage and buffer tank) (Square Meter)

L : Available space for biomass and backup boilers (including storage and buffer tank) (Square Meter)

m : Number of air pollution criteria

$e_j(x^{(t)}, y^{(t)})$: Aggregated air pollutant '*j*' emission from biomass and backup boilers at period '*t*' (kg/Month)

E_j : Allowance (standard) for air pollutant '*j*' emission (kg)

$e(x^{(t)}, y^{(t)})$: Carbon savings achieved at period '*t*' (kg/Month)

E_0 : Carbon saving target (kg)

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Figures

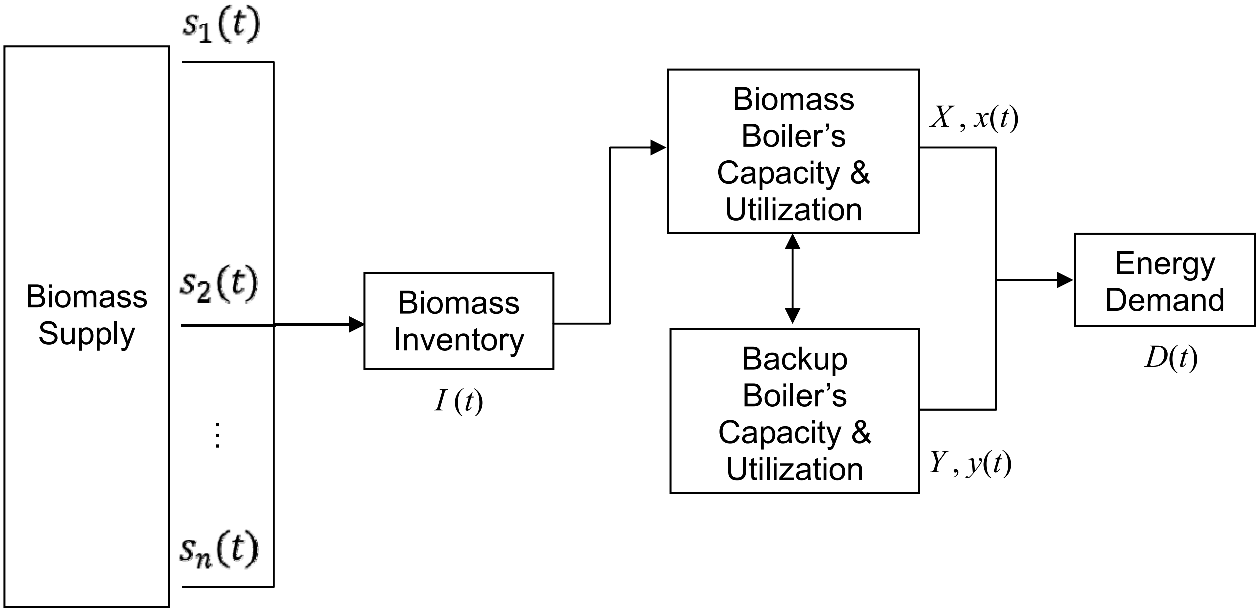

Figure 1 – A graphical representation of the proposed model with purchase, capacity, and utilization decision variables governed by biomass inventory and energy demand levels

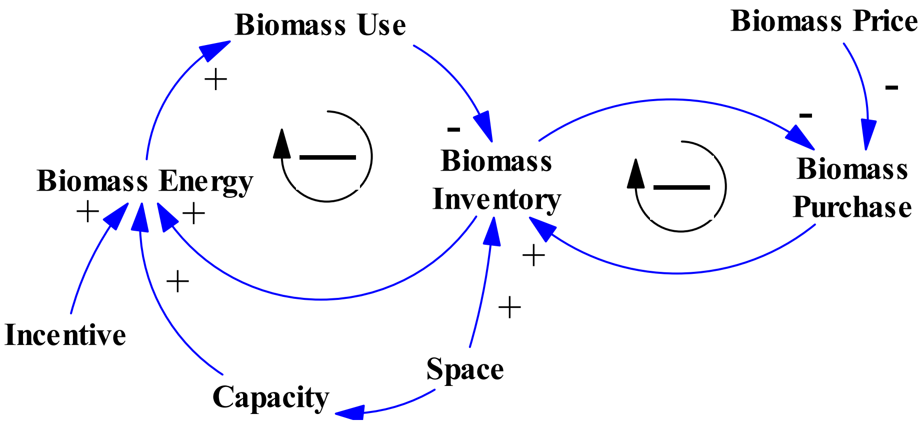

Figure 2 – Asset management and supply chain causal loops governing a biomass boiler’s performance

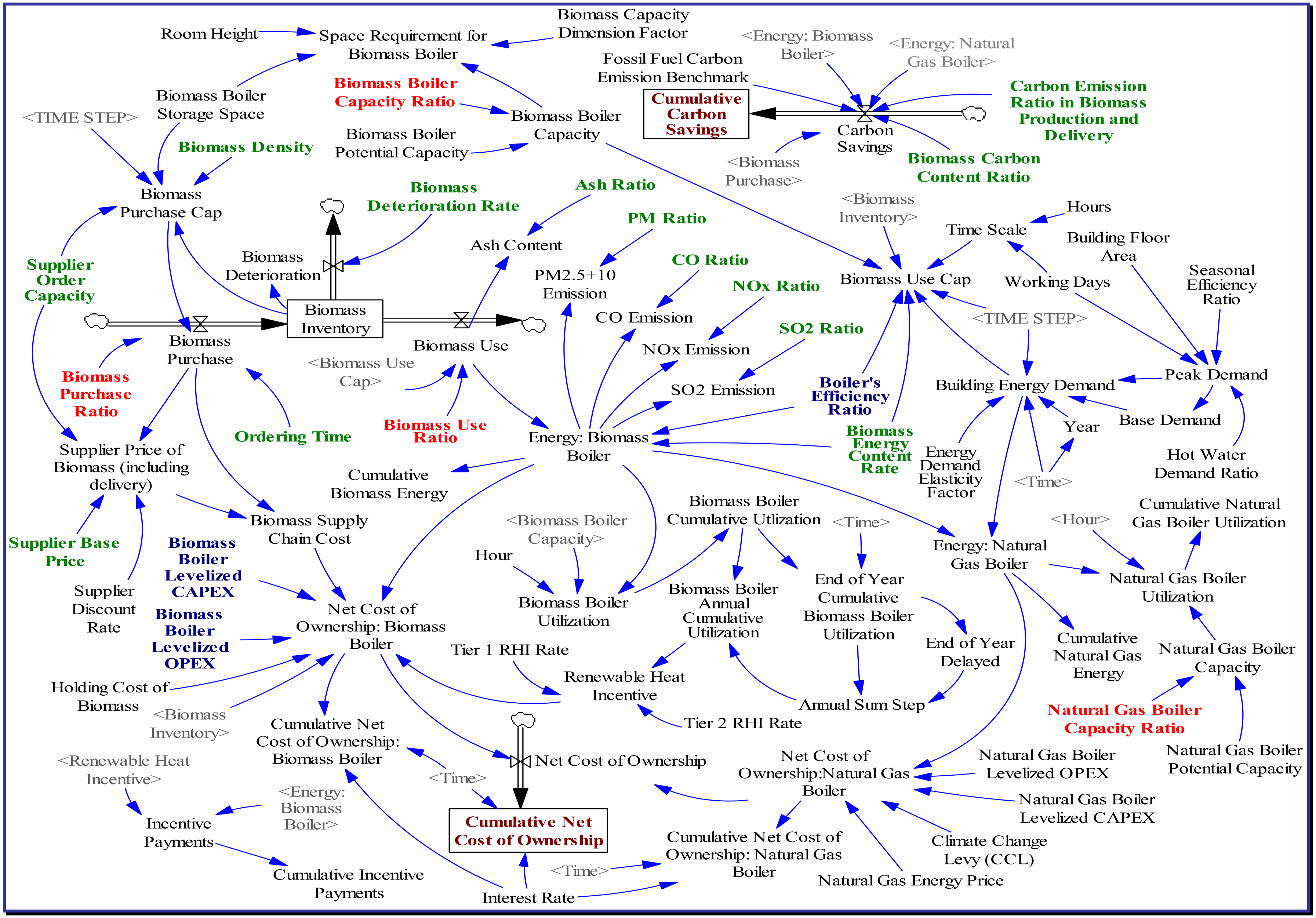

Figure 3 – A whole life supply chain-asset management model for non-domestic biomass boilers

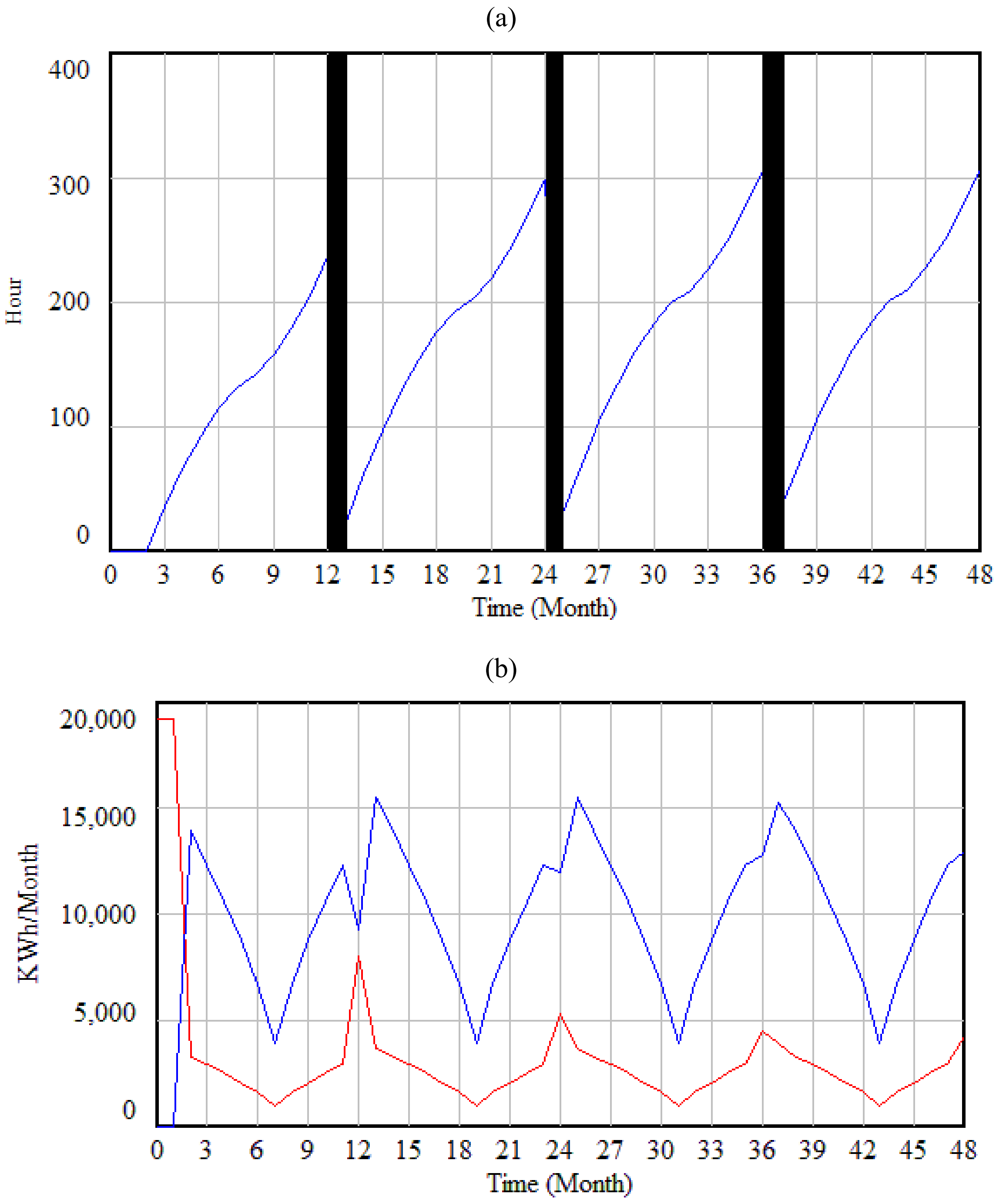

Figure 4 – Optimal operational plan: (a) cumulative biomass boiler's utilization per year (hour) and (b) energy (heat) generation plan from biomass and back-up boilers (KWh/Month)

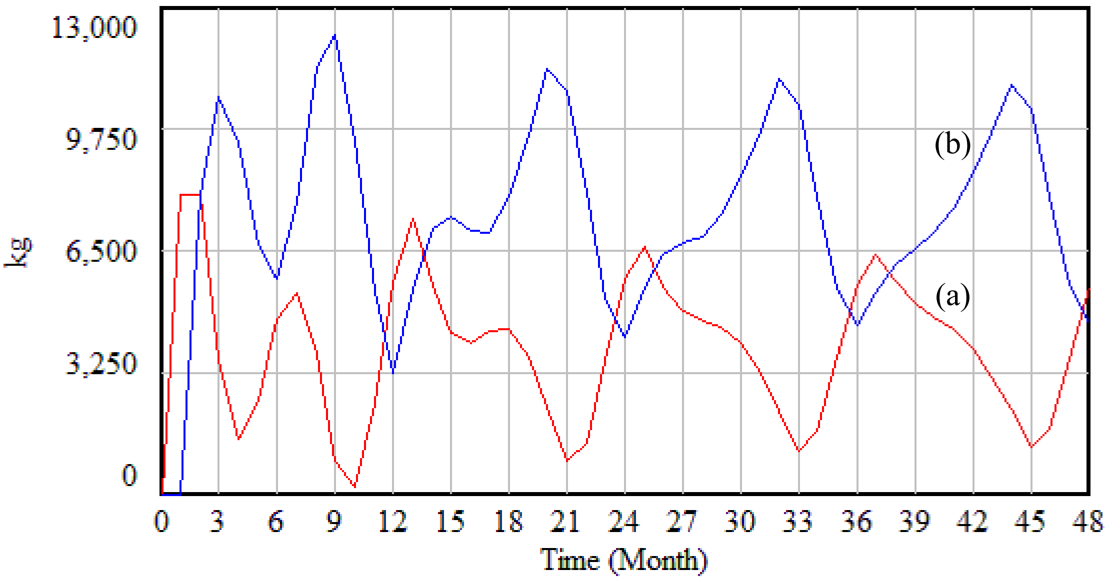

Figure 5 – Optimal biomass (a) ordering and (b) inventory plans

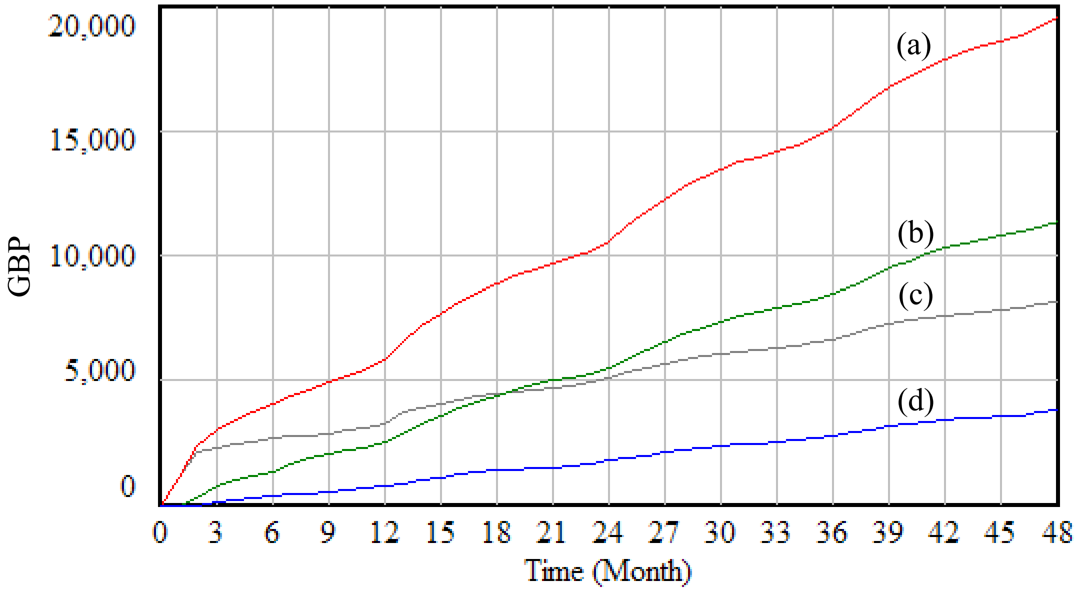

Figure 6 – Transition to biomass (a) cumulative net total cost, (b) cumulative net cost of biomass boiler, (c) cumulative net cost of back-up boiler, and (d) cumulative renewable heat incentive payment

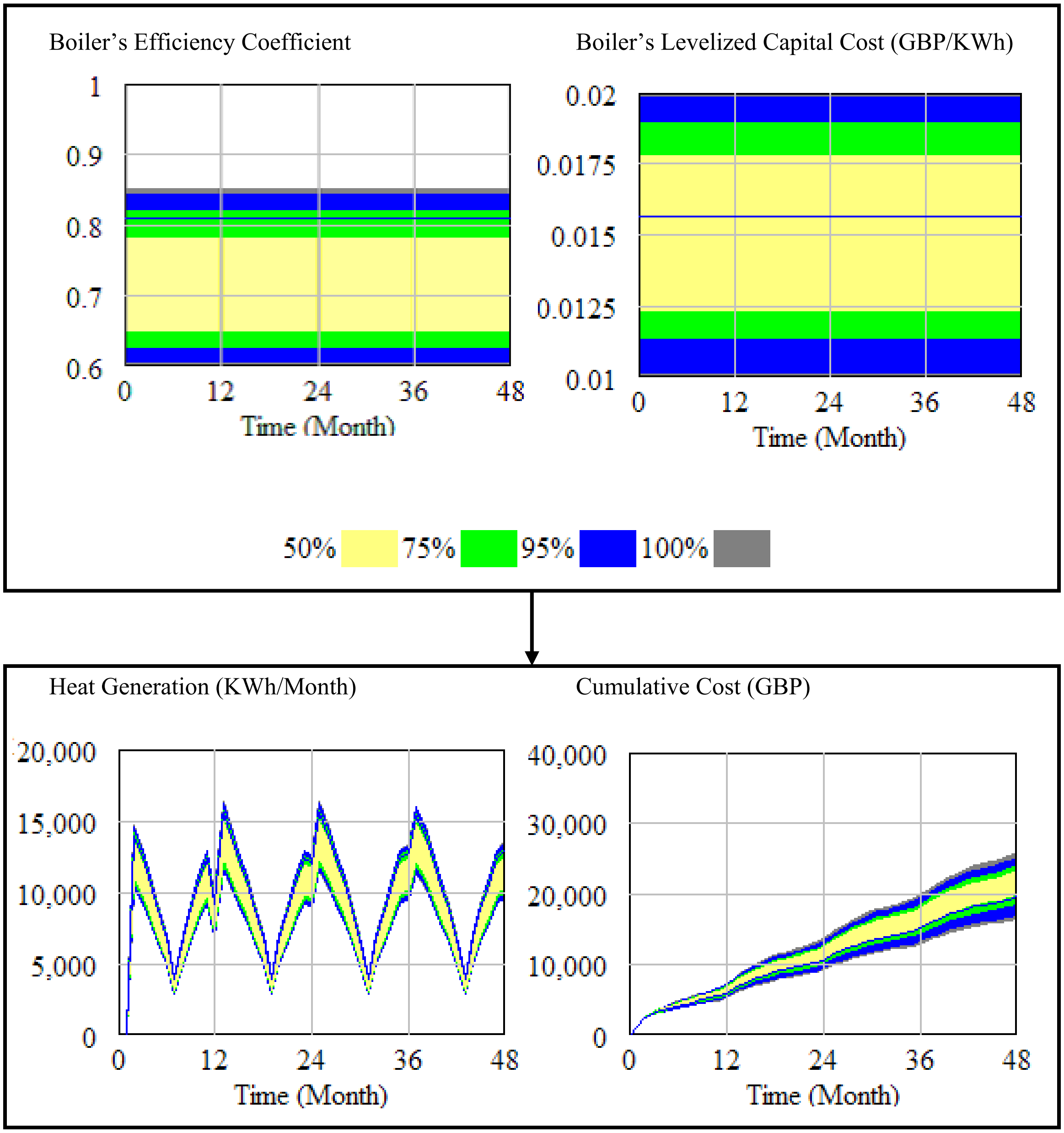

Figure 7 – Sensitivity of biomass energy (heat) generation and cumulative cost to choice of biomass boiler's technology with variations in efficiency and price (capital cost)

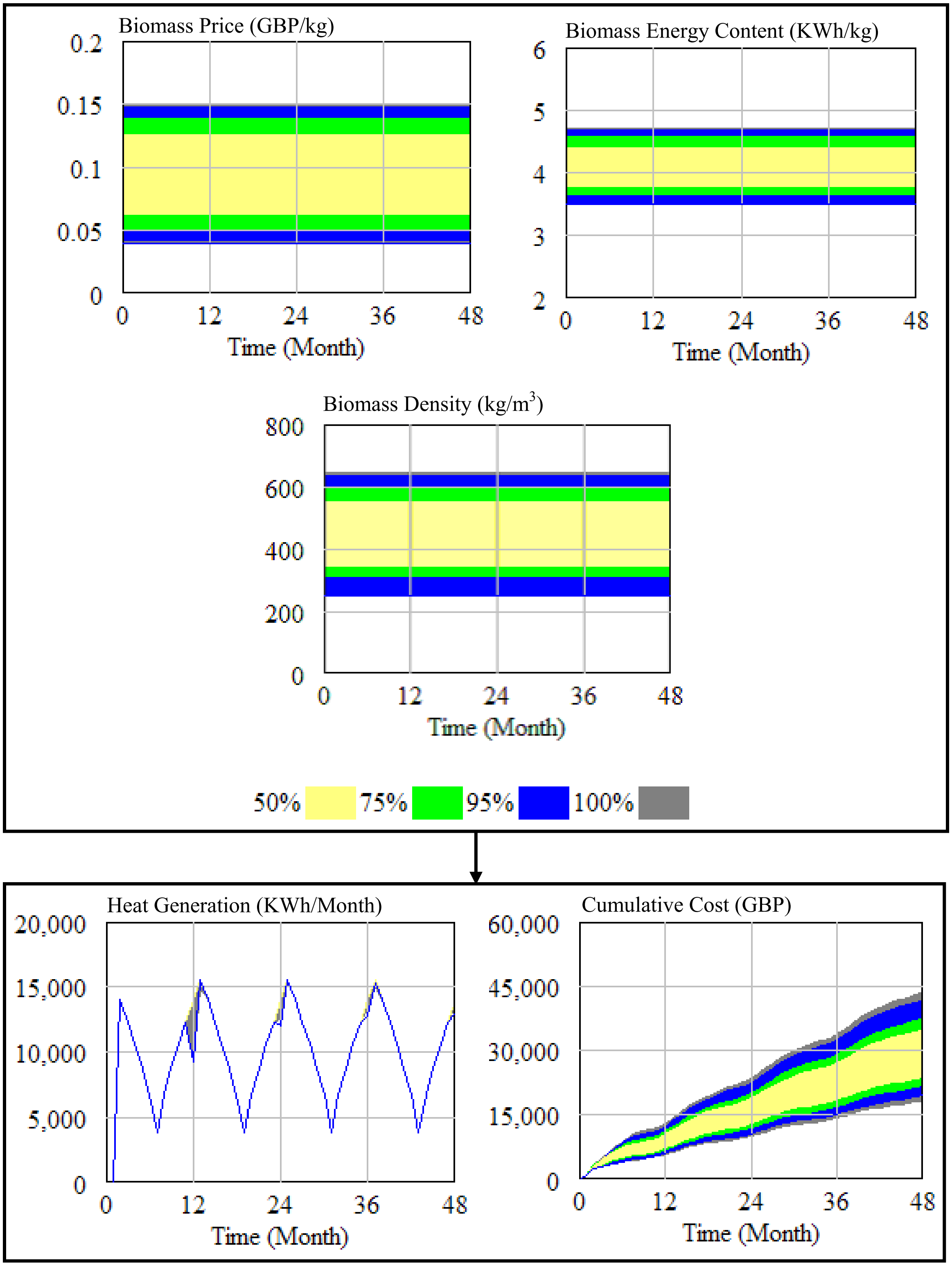

Figure 8 - Sensitivity of biomass energy (heat) generation and cumulative cost to choice of biomass materials with variations in price, energy content and density

Tables

Table 1 – Renewable heat incentive structure for non-domestic applications

Technology	Capacity (KW)	Use (Hours)	Incentive (GBP/KWh)
Biomass Boilers	< 200	< 1,314	0.086
		> 1,314	0.022
	200<<1000	< 1,314	0.05
		> 1,314	0.021
	> 1000	-	0.01
Heat Pumps	< 100	-	0.048
	> 100	-	0.035
Solar	-	-	0.092
Biogas	-	-	0.073

Table 2 – Biomass fuel’s range of options

Source	**Price (£/kg)**	**Energy Content (KWh/kg)**	**Density kg/m^3**
Woodchip	0.04	3.5	250
Wood Pellet	0.15	4.7	650

Appendix

A description of the equations, variables, and parameters as appeared in Vensim platform:

Annual Sum Step= INTEG (End of Year Cumulative Biomass Boiler Utilization-End of Year Delayed,0) Units: Hour
Ash Content= Biomass Use*Ash Ratio/100 Units: kg/Month
Ash Ratio=4.5 Units: Dmnl
Base Demand=0.25*Peak Demand Units: KWh/Month
Biomass Boiler Annual Cumulative Utilization=Biomass Boiler Cumulative Utlization-Annual Sum Step Units: Hour
Biomass Boiler Capacity=Biomass Boiler Capacity Ratio*Biomass Boiler Potential Capacity Units: KW
Biomass Boiler Capacity Ratio=1 Units: Dmnl
Biomass Boiler Cumulative Utlization= INTEG (Biomass Boiler Utilization,0) Units: Hour
Biomass Boiler Levelized CAPEX=0.01562 Units: GBP/KWh
Biomass Boiler Levelized OPEX=0.00259 Units: GBP/KWh
Biomass Boiler Potential Capacity=400 Units: KW
Biomass Boiler Storage Space=50 Units: Cubic Meter
Biomass Boiler Utilization=Hour*"Energy: Biomass Boiler"/Biomass Boiler Capacity Units: Hour/Month
Biomass Capacity Dimension Factor=1 Units: Square Meter/KW
Biomass Carbon Content Ratio=0.006 Units: kg/KWh
Biomass Density=250 Units: kg/Cubic Meter
Biomass Deterioration=Max(Biomass Deterioration Rate*Biomass Inventory,0) Units: kg/Month
Biomass Deterioration Rate=0.05 Units: 1/Month
Biomass Energy Content Rate=3.5 Units: KWh/kg
Biomass Inventory= INTEG (Biomass Purchase-Biomass Use-Biomass Deterioration,0) Units: kg
Biomass Purchase= DELAY FIXED (Biomass Purchase Ratio*Biomass Purchase Cap, Ordering Time , 0) Units: kg/Month
Biomass Purchase Cap=Max(MIN ((Biomass Boiler Storage Space*Biomass Density-Biomass Inventory)/TIME STEP,Supplier Order Capacity),0) Units: kg/Month
Biomass Purchase Ratio=0.7981 Units: Dmnl
Biomass Supply Chain Cost="Supplier Price of Biomass (including delivery)"*Biomass Purchase Units: GBP/Month
Biomass Use=Max(Biomass Use Ratio*Biomass Use Cap,0) Units: kg/Month
Biomass Use Cap=Max(MIN (MIN(Time Scale*Biomass Boiler Capacity*Boiler's Efficiency Ratio, Building Energy Demand)/Biomass Energy Content Rate, Biomass Inventory/TIME STEP),0) Units: kg/Month
Biomass Use Ratio=1 Units: Dmnl
Boiler's Efficiency Ratio=0.81 Units: Dmnl
Building Energy Demand=IF THEN ELSE(Time > 0, Base Demand+(Peak Demand-Base Demand)*ABS((Time-1)/TIME STEP/6-2*Year+1)^Energy Demand Elasticity Factor, Peak Demand) Units: KWh/Month
Building Floor Area=12000 Units: Square Meter
Carbon Emission Ratio in Biomass Production and Delivery=0.02315 Units: kg/kg
Carbon Savings=(Fossil Fuel Carbon Emission Benchmark-Biomass Carbon Content Ratio)*"Energy: Biomass Boiler"-Carbon Emission Ratio in Biomass Production and Delivery*Biomass Purchase-Fossil Fuel Carbon Emission Benchmark*"Energy: Natural Gas Boiler" Units: kg/Month
"Climate Change Levy (CCL)"=0.00182 Units: GBP/KWh
CO Emission= CO Ratio*"Energy: Biomass Boiler" Units: kg/Month
CO Ratio=3000/(1000*277.778) Units: kg/KWh
Cumulative Biomass Energy= INTEG ("Energy: Biomass Boiler",0) Units: KWh
Cumulative Carbon Savings= INTEG (Carbon Savings,0) Units: kg

Cumulative Incentive Payments= INTEG (Incentive Payments,0) Units: GBP

Cumulative Natural Gas Boiler Utilization= INTEG (Natural Gas Boiler Utilization,0) Units: Hour

Cumulative Natural Gas Energy= INTEG ("Energy: Natural Gas Boiler",0) Units: KWh

Cumulative Net Cost of Ownership= INTEG (Net Cost of Ownership/(1+Interest Rate/100)^Time,0) Units: GBP

"Cumulative Net Cost of Ownership: Biomass Boiler"= INTEG ("Net Cost of Ownership: Biomass Boiler"/(1+Interest Rate/100)^Time,0) Units: GBP

"Cumulative Net Cost of Ownership: Natural Gas Boiler"= INTEG ("Net Cost of Ownership:Natural Gas Boiler"/(1+Interest Rate/100)^Time,0) Units: GBP

End of Year Cumulative Biomass Boiler Utilization=IF THEN ELSE(Time/12=INTEGER(Time/12), Biomass Boiler Cumulative Utlization, 0) Units: Hour

End of Year Delayed= DELAY FIXED (End of Year Cumulative Biomass Boiler Utilization, 12 , 0) Units: Hour

Energy Demand Elasticity Factor=0.8 Units: Dmnl

"Energy: Biomass Boiler"=Biomass Use*Biomass Energy Content Rate*Boiler's Efficiency Ratio Units: KWh/Month

"Energy: Natural Gas Boiler"=Building Energy Demand-"Energy: Biomass Boiler" Units: KWh/Month

Fossil Fuel Carbon Emission Benchmark=0.194 Units: kg/KWh

Holding Cost of Biomass=0.001 Units: GBP/kg

Hot Water Demand Ratio=0.002 Units: KWh/Square Meter

Hour=1 Units: Hour*KW/KWh

Hours=24 Units: KWh/KW

Incentive Payments="Energy: Biomass Boiler"*Renewable Heat Incentive Units: GBP/Month

Interest Rate=2.5/12 Units: Dmnl

Natural Gas Boiler Capacity=Natural Gas Boiler Capacity Ratio*Natural Gas Boiler Potential Capacity Units: KW

Natural Gas Boiler Capacity Ratio=0.934 Units: Dmnl

Natural Gas Boiler Levelized CAPEX=0.00607 Units: GBP/KWh

Natural Gas Boiler Levelized OPEX=0.00079 Units: GBP/KWh

Natural Gas Boiler Potential Capacity=100 Units: KW

Natural Gas Boiler Utilization=Hour*"Energy: Natural Gas Boiler"/Natural Gas Boiler Capacity Units: Hour

Natural Gas Energy Price=0.0458 Units: GBP/KWh

Net Cost of Ownership="Net Cost of Ownership: Biomass Boiler"+"Net Cost of Ownership:Natural Gas Boiler" Units: GBP/Month

"Net Cost of Ownership: Biomass Boiler"=(Biomass Boiler Levelized CAPEX+Biomass Boiler Levelized OPEX-Renewable Heat Incentive)*"Energy: Biomass Boiler"+Biomass Supply Chain Cost+Holding Cost of Biomass*Biomass Inventory Units: GBP/Month

"Net Cost of Ownership:Natural Gas Boiler"="Energy: Natural Gas Boiler"*(Natural Gas Boiler Levelized OPEX+Natural Gas Boiler Levelized CAPEX+Natural Gas Energy Price+"Climate Change Levy (CCL)") Units: GBP/Month

NOx Emission=NOx Ratio*"Energy: Biomass Boiler" Units: kg/Month

NOx Ratio=150/(1000*277.778) Units: kg/KWh

Ordering Time=1 Units: Month

Peak Demand=24*Hot Water Demand Ratio*Building Floor Area*Working Days/Seasonal Efficiency Ratio Units: KWh/Month

PM Ratio=76/(1000*277.778) Units: kg/KWh

"PM2.5+10 Emission"=PM Ratio*"Energy: Biomass Boiler" Units: kg/Month

Renewable Heat Incentive=IF THEN ELSE(Biomass Boiler Annual Cumulative Utilization <= 1314, Tier 1 RHI Rate, Tier 2 RHI Rate) Units: GBP/KWh

Room Height= 3.9 Units: Meter

Seasonal Efficiency Ratio=0.75 Units: Dmnl

SO2 Emission=SO2 Ratio*"Energy: Biomass Boiler" Units: kg/Month

SO2 Ratio=20/(1000*277.778) Units: kg/KWh

Space Requirement for Biomass Boiler=80.99+31.46*LN(Biomass Capacity Dimension Factor*Biomass Boiler Capacity/1000)+Biomass Boiler Storage Space/Room Height Units: Square Meter

Supplier Base Price=0.04 Units: GBP/kg

Supplier Discount Rate=0.1 Units: Dmnl

Supplier Order Capacity=10000 Units: kg/Month

"Supplier Price of Biomass (including delivery)"=Supplier Base Price*(1-Supplier Discount Rate*(Biomass Purchase/Supplier Order Capacity)) Units: GBP/kg

Tier 1 RHI Rate=0.05 Units: GBP/KWh

Tier 2 RHI Rate=0.021 Units: GBP/KWh

Time Scale=Working Days*Hours Units: KWh/(KW*Month)

TIME STEP = 1 Units: Month

Working Days=25 Units: 1/Month

Year=IF THEN ELSE(Time/12 = INTEGER(Time/12) :AND: Time>0, INTEGER(Time/12), INTEGER(Time/12)+1) Units: Dmnl