Predicting warm efficiency of insulation materials in actual space based on data collected by intelligent temperature control system

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***Abstract*—Staying warm is a major source of carbon emissions. In order to reduce carbon emissions for heating, scientists are working to develop cleaner heating energy, cleaner power generation, and more energy-efficient heating facilities, but using insulation materials to reduce the use of heating facilities is also a way to reduce carbon emissions. In this project, we designed a smart control system to adjust room temperature and collect data from the real world. Then, fitting data into a supervised learning model to predict warm efficiency for a building in an application called Heating Planner. This application simulates the use of insulation in housing, through which users can learn about the benefits of using insulation materials on keeping warm and reducing carbon emissions. We showed the prototype to the interviewees and collected feedback and suggestions. In conclusion, our application can contribute to "Zero Carbon Emissions in staying warm".**

Keywords—staying warm, zero-carbon emission, smart control system, supervised learning, insulation material, housing, prototype, application.

I. THE PROBLEM AREA

The long-term changing of Earth's temperature and weather patterns is known as climate change. To persuade the great majority of scientists that human activity might change the climate of our whole world, it required nearly a century of investigation and evidence. The 1800s saw more interest that anxiety in response to studies that suggested human-produced carbon dioxide and other gases may build up in the atmosphere and insulate Earth. Carbon dioxide measures would provide some of the first evidence to support the notion of global warming by the late 1950s [1]. Eventually, a wealth of data, climate modelling, and actual weather occurrences would demonstrate not just the reality of global warming but also the myriad of disastrous effects it would have.

The website of the United States Environmental Protection Agency has a pie chart of global emissions by economic sector. The graph shows that the burning of coal, natural gas, and oil for electricity and heat is the largest single source of global greenhouse gas emissions. This 25% of global greenhouse emissions only covered the electricity and heat production sector. There is 6% of greenhouse gas emissions from the building include onsite energy production and fuel combustion for cooking or heating [2]. While another pie chart shows that carbon dioxide accounts for 65% of the global greenhouse gases released by human activities [2]. It is easy to see that the carbon emissions from people's daily heating are a significant part of the total carbon emissions.

II. CHALLENGE CHOSEN AND WHY IT WAS CHOSEN

Since heat-producing sectors around the world are emitting large amounts of greenhouse gases into our living environment, one of the largest contributors to each of our personal carbon footprints is the energy consumed to heat the places where we live. Moreover, BBC news reported that nearly 50% of energy-related carbon emissions are caused by heating [3]. Although your living location will determine exactly how much of your personal emissions are caused by heating your home, and this percentage tends to be much higher in areas with cooler temperatures like Canada and Russia. Carbon emissions from heating are seriously harming the environment and contributing to the greenhouse effect, so the challenge is to reduce or even eliminate carbon emissions from heating.

III. EXISTING SOLUTIONS AND MEASURES

Since people realized that carbon emissions from heating are harmful to the environment, all sectors of society have been working to reduce carbon emissions from heating. Scientists are committed to researching cleaner heating energy sources. Governments have provided funding for projects to reduce carbon emissions from heating, and regulations have been established for reducing carbon emissions from heating. In addition, heat pumps are also being promoted as a heating device that produces fewer carbon emissions than traditional

heating with electric furnaces. In order to reduce the carbon footprint of heating from the energy and production point of view, there is another way which is to reduce the heating demand of buildings, and this brings us to insulation materials.

A. Cleaner heating energy sources

Nowadays, natural gas is still the most often utilized fuel type for home heating. About 47% of American houses utilize it. While 36% of people use electricity as their main space heating source [4]. However, natural gas is a non-renewable energy source, and electricity production is one of the largest sources of carbon emissions. Therefore, we have to find a cleaner and more renewable source for heating. Here, we can use clean energy to generate electricity and then use electric heating facilities. So, the carbon emission from heating is reduced. There are several cleaner energy sources, for example, solar, wind, and biomass.

Solar is one of the most well-known clean energy sources, it has the potential to produce clean, almost endless energy, whether it is utilized directly in a thermal system, converted to electricity using a photovoltaic cell, or transformed using a concentrator technology [18]. Wind power is another green and renewable clean energy.

Wind turbines use the mechanical energy of the wind to turn a generator and produce electricity. In addition to being a plentiful and limitless resource, wind also generates power without consuming any fuel or damaging the environment. In the United States, wind energy helps save 329 million metric tonnes of carbon emissions, which is the same amount of emissions produced by 71 million cars and contributes to acid rain, pollution, and greenhouse gas emissions [19].

Plant matter, such as trees, grass, agricultural crops, or other biological materials, is referred to as biomass. Energy is kept in biomass. Photosynthesis is the process through which plants use the sun's energy to absorb it and transform it into chemical energy. Burning plants or other organic things releases this energy as heat. It can be used as a solid fuel or transformed into liquid or gaseous forms to produce heat [5].

One of the advantages of using biomass for heating is highly efficient in that as much as 85% of the energy contained in the fuel can be used by the user when using biomass for heating. Also, utilizing by-products and waste streams is another advantage. Since most biomasses are coming from the waste stream and by-products of other businesses [6]. The most important advantage of using biomass is that biomass is a dispatchable and renewable source that can be stored and used when needed. Unlike solar energy which is unavailable when the sun is not shining. Biomass always meets the heating demands of both homes and businesses [6].

B. Government policies

Technology can help to reduce carbon emissions by inventing cleaner sources for heating. While the government also plays an important role. For example, in the report called 2030 Emissions Reduction Plan – Canada's Next Steps for Clean Air and Strong Economy, the Government of Canada plans to achieve an emissions reduction target of 40% to 45% below 2005 levels by 2030 and to achieve net-zero emissions by 2050 [7]. One of the measures is increasing renewable and non-emitting energy sources for power generation and heating production. Also, carbon emission from heating buildings accounts for 12% of total carbon emissions. Buildings and communities in a low-carbon, the clean-growth economy will be incredibly energy-efficient, rely on clean power and renewable energy, and be smart and sustainable.

In order to reduce carbon emissions from heating, the government will not only enact relevant policies and plans but also invest funds. For example, in an effort to minimize carbon emissions from house heating, Ontario invested $92 million in its retrofitting in 2016. This included installing energy-efficient boilers and insulating exterior walls. In order to expand on this initial investment, Ontario's Climate Change Action Plan has committed an additional $500 million for retrofits of buildings over the following five years [7]. There is another example on Prince Edward Island in Canada. The longest-running district heating system in Canada, powered by biomass, is located on Prince Edward Island. The system, which has been in operation since the 1980s and now serves over 125 buildings in Charlottetown's downtown center, including the University of Prince Edward Island and the Queen Elizabeth Hospital, safely burns 66,000 tonnes of trash each year [7]. Heating with biomass combustion has been successful on a regional scale. If this type of heating can be extended to the whole country, the carbon emissions produced from heating will be greatly reduced in Canada.

C. Heat pump

Although it is a stereotype, the freezing winters in Canada are real. And a lot of people keep warm by using fossil fuels like natural gas to heat homes, either in furnaces or the boilers that supply radiators. However, using natural gas to keep warm leads to greenhouse gas emissions. According to an article from CBC News, using fossil fuels to produce energy, such as heat and electricity, results in around 45% of Canada's carbon emissions, which is much greater than transportation. About 50% of that comes from homes, businesses, schools, and other private and public structures [8]. Another 50% is from the industry. Statistics Canada reported that the majority of the basic heating systems in Canada are forced air furnaces and hot water or steam boilers with radiators, which typically use fossil fuels like natural gas [9]. Natural gas is not renewable energy and using it as a heating source of energy will produce a large number of greenhouse gases.

There is a more efficient and eco-friendly option for staying warm. The heat pump is an electrically powered device that transfers heat from a source of low temperature to a target area of higher temperature. Natural heat flow is when heat moves from a hot place to a cold place. In order to counteract the natural flow of heat and move energy present in a cold place to a hot place, a heat pump needs additional electrical energy [10]. Also, there are several types of heat pumps, like an air-source heat pump, which transfers heat from outside into buildings, and a ground-source heat pump, which generates heat from the soil, groundwater, or both into buildings. Although a heat pump is an electrically powered device, it is more efficient than a furnace and boiler because these two heating facilities cannot 100% of their energy to heat buildings. The working principle of heat pumps is different. The heat energy is transferred between two sites using the heat pump's input of electricity. Due to this, heat pumps typically run at an efficiency well above 100%, meaning that more thermal energy is generated than is required to pump the heat [10].

Phased Heat Pump Retrofit as Part of City's Long Term Capital Planning to Achieve Zero Emissions in All Buildings is a case study done in Vancouver. It represented that the City of Vancouver plans to achieve 100% renewable energy and

zero emission in its own facilities by 2040. In this case study, an air source heat pump is the main technology, and phase I is from 2014 to fall 2017, and phase II is from 2018 to 2019. The estimated annual savings in phases I and II are very sustainable. Gas has saved 2,000 GJ, electricity has saved 110,000 kWh, and greenhouse gas emissions have been reduced by 34% [20].

D. Insulation materials

Using clean energy as a heating source, establishing policies and providing funds by the government, and using more energy-efficient heating facilities can reduce carbon emissions from heating in different ways, but increasing buildings' energy efficiency is also an approach that cannot be ignored. Christoph Reinhart, head of the MIT building technology department, told that a building's main function is to give shelter. Being thermally isolated and lowering conduction is always a positive thing [11]. Building insulation is regarded as a straightforward yet incredibly effective energy-saving strategy that may be used in residential. A substance or combination of materials with high thermal resistance, which has the capacity to slow down the transfer of heat, makes up a thermal insulator [12]. Building insulation can thereby preserve heat inside while preventing heat transfer to the outside [13]. Various materials, including fiberglass, mineral wool, foam, and others, are frequently employed as insulation materials. Building insulation also offers significant cost savings. This is possible because some of the building insulations help to maintain a positive net energy balance by allowing for greater energy savings during insulation application that during the material's actual production [13].

Nowadays, there are many different insulation materials on the market. Some of them have great thermal insulation, but their production process and disposal process will produce a lot of carbon emissions. There are lots of natural, eco-friendly, and renewable sources combined with each other that can be a great insulation material, for example, clay served as the filter, water-based paint binder served as the binder, and the fiber utilized were sheep wool, kenaf, and wheat straw. Moreover, many new materials have been found to have good thermal insulation and do not produce much carbon emissions. Due to its intriguing qualities, including availability, low toxicity, natural abundance versatile surface chemistry, and biodegradability, nano cellulose is now a material of great interest [14]. Thermal insulation made of cellulose nanofibers, which were from cotton, and hydrolyzed in sulfuric acid, then subjected to ultrasonication, has lower thermal diffusivity and thermal conductivity value [14]. Therefore, cellulose nanofibers can be marketed as environmentally friendly, low-carbon, and effective insulation materials.

Just like cellulose nanofibers, there are many new green insulation materials that exist but are not well-known. To make people aware of the properties of these new, green insulation materials and use them, a professional promotion platform is needed.

IV. Solution and Prototype

Based on what we discussed above, green insulation materials need to be a chance to be known by people. The solution is generated from our sprint idea, which is a combination of the smart control system and insulation. The solution is providing a service that supports people designing the heating part of buildings. The aim of this solution is to support people in controlling the carbon emissions from building heating.

The solution is named Heating Planner which has two key points. The first key point is about a smart control system that is used to detect energy for heating in real-time. The name of it is HP (heating planner) smart control system. During the Sprint process, we made the customer needs and devised a metric corresponding to the needs.

TABLE I. Customer Need

No.		Need	Imp.
1	The smart control system	Can control the temperature automatically	3
2	The smart control system	Can make the heating facilities use energy more efficiently to decrease the carbon emissions	4
3	The heating planner application	Can simulate the installation of insulation materials.	3
4	The heating planner application	Can provide the visualization of the building.	2
5	The heating planner application	Can generate a warm efficiency report for each insulation plan	3
6	The heating planner application	Can generate a carbon emission report for each insulation plan	5
7	The heating planner application	Can provide a detailed introduction for each insulation material, such as thermal conductivity, etc.	2

TABLE II. Needs Metrics and Units

Metric No.	Need No.	Metric	Imp.	Units
1	1	Building location	4	formal address
2	1	Room area	4	m^2
3	1,2	Room temperature preference	5	Celsius
4	1	Insulation material selection	4	material name
5	1,2	Heating facilities usage	4	hours per day
6	5	Warm efficiency	4	%
7	6	Carbon emission	5	Metric ton
8	7	Thermal conductivity	3	W/mK
9	4	Scale of the 3D model	2	Pixel/meter

Based on these needs metrics, the HP smart control system can automatically change the set temperature to keep the user's

home always at a suitable temperature. Moreover, the HP smart control system can collect data from the user's house, then calculate the results by applying analytical algorithms, which is important to the second key point of our solution. Users are required to install an application in order to use this smart control system. After the user registered the application, they are required to provide the basic information, such as building location, room area, room temperature preference, heating facilities usage, and the insulation materials that they applied to their houses. For these users who live in apartments, we not only collect information on whether they have installed additional insulation materials during renovation, but we also work with the apartment contractors to get the breakdown of the insulation materials installed in the apartment. This way, the data we have is more accurate. Then, the smart control system is able to collect user-provided data and fit it into an analytical model. It is a machine learning model that utilizes supervised learning, which uses a database with input and output to train the model that makes a prediction. In our project, this analytical model can calculate the insulation ability of the user's house. For example, user A's house is 2,400 square feet. He has installed four types of insulation materials in his home, such as sheep wool, perlite, glass wool, and cellulose wadding. His major heating facility is a modern high-efficiency electric furnace. He opens his electrical furnace 4 hours per day to keep the room temperature at 26 Celsius. The electric furnace needs 18 kilowatts per hour for heating. Based on these data, our model can calculate heat efficiency. The smart control system is able to capture the room temperature, and then we can know the heat loss rate of his house. Finally, the model can calculate the warm efficiency of his house. In our project, warming efficiency refers to the ability of a house to maintain temperature after considering heating efficiency and insulation efficiency. Thus, the main purpose of the smart control system is to collect data, prepare for modeling, and continue delivery of the output such as warm efficiency and carbon emissions of the building.

The second key point is about an application bundled with the HP smart control system. The application is named as Heating Planner application. This application is supposed to provide visualization and interaction for users and focused on insulation materials. In this section, a brief description of this application is given. Firstly, the application has a normal register and a login page. The application requires the user to choose the building type, such as apartment or house. Also, they are allowed to input the house/apartment size, and room plan, like four bedrooms and two washrooms of his/her home. Then, the application will set up a 3D model, based on the data collected from the HP smart control system, of a house or apartment according to the user's previous selection. Users can select to see each room of the building. To do this function, the application automatically invokes APIs of the HP smart control system to build the 3D model of the building. For example, the application makes a call of a GET method to request the data of a room area. Then the response of the smart control system will respond to the relative data in JSON format. Since the 3D model is composed of each room, the user can have a visualization of the house. Once the 3D model is available to the user, then he/she is able to apply insulation materials to each part of the house. We put insulation materials below the 3D model, and users are allowed to scroll down the page to find each of them. Users can apply different insulation materials in different parts of the room. Also, they are allowed to change their minds by removing selected insulation materials from where it has been applied and then applying another one on it. After the user feels satisfied with his/her selection, he/she can save the plan. And the application is able to invoke the smart control system automatically. Then our analytical algorithm will help to generate a report and display the percentage of warm efficiency in the user's home based on his/her plan. Moreover, the report also displays the carbon emissions of the building. The purpose of this feature is to subconsciously make users aware of environmental protection and remind them to pay attention to carbon emissions. The report continues updated in a short time period because the analytical algorithm continues running in the smart control system. This feature is similar to a real-time delivery approach. Additionally, there is a page that lists all the insulation materials. The user can choose any of the insulation materials from the list.

There are more features in this application. As part of the UX design, the application allows users to select different insulation materials by dragging them to relative parts of the building. For example, the user is able to tap and hold on to the icon of coconut fibers, then it can be dragged to the roofing part of the house. After the user finishes the step of choosing insulation materials, the application can save it as a plan and the application can also generate the warm efficiency of the house based on this plan. Moreover, the application can generate a few recommended plans for the user by considering users' preferences on insulation materials selection, users' home location, and the building type. Each plan shows the warm efficiency in a pie chart, and every pie chart is composed of the percentage of selection materials. Users can tap and hold on to any part of the pie chart to see the percentage of specific insulation material used in this plan. Also, they are allowed to save different selections as different plans. Then, they can compare these plans to see the differences between each other. From the comparison, users can review the advantages and disadvantages of each plan intuitively.

Another feature of the application is the collection of all insulation material. There is a page to display all the insulation materials we have. These insulation materials include but are not limited to coconut fibers, reeds panels, cellulose wadding, foam glass, straw, glass wool, perlite, sheep wool, wood fiber, and green roof. Users can browse all of the materials from the list. In addition, by clicking the icon of insulation materials, users can see detailed information about these insulation materials including the manufacturing processes, thermal conductivity, properties, and conditions of use, as well as the picture.

V. FEEDBACK

There are several important points that we should pay attention to after summarizing the feedback from the interviewees. The first one is insulation material selection. We made a pie chart (Figure 1) according to the feedback from the interview, top three selected insulation materials are glass fiber, mineral wool, and hemp. Among those materials, glass fiber and hemp are both environmentally friendly insulation materials. In contrast, mineral wool insulation is not environmentally friendly because the melted stone is used to create mineral wool, while the stone is not a renewable resource. It has a high embodied energy and is produced using a lot of energy. Gas and coal are used on-site throughout the production process in furnaces, boilers, and dryers. The furnace must burn continuously, day and night, throughout the

whole year, to melt the stone at extremely high temperatures [15]. Thus, the production process of mineral wool produces a large number of carbon emissions. However, it is a commonly used insulation material because there is a lot of publicity for mineral wool both online and offline. Thus, people are familiar with it. If we put green insulation materials in our app, people will be more familiar with them, and then they are more likely to choose these green insulation materials.

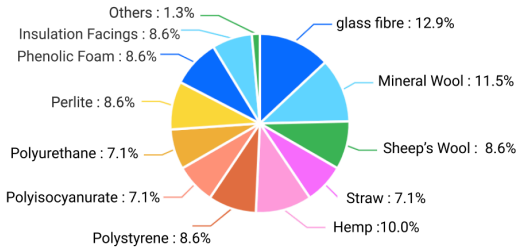

Fig. 1. Insulation Material Selection (*During the interview, we asked that "what insulation materials do you know". This pie chart shows the interviewees' responses.*)

Also, when we asked our interviewees what is the most care point when they select insulation materials. As Fig. 2 shows that from the feedback we know that durability is one of the most important points for our interviewees when they choose insulation materials. Not only does durable insulation material save a lot of money in maintenance and replacement costs for people, but it also plays an important role in protecting the environment. The definition of durability is that durability is the ability to last a long time without significant deterioration. Durable materials help the environment by conserving resources to reduce waste and the environmental impacts of repair and replacement material. When interviewees were asked about the difficulties that they encountered in choosing insulation materials, they felt that the most difficult part was balancing the price and quality of the insulation. While the second was whether the selected insulation material has potential harm to humans. So, some of our interviewees mentioned that we should include the composition and toxicity of each insulation material in our application.

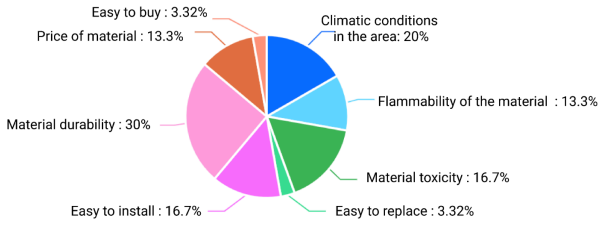

Fig. 2. Characteristics of the insulation materials of care (*During the interview, we asked that "How do you select insulation materials", and this pie chart shows the interviewees' responses.*)

It is pleasant to note that our interviewees largely agreed that our application is a great platform to introduce insulation materials. Firstly, it can bring basic knowledge about insulation materials to the public, and people will have some basic cognition of the advantages of installing insulation materials. Also, our application contains not only introductions of multiple insulation materials, but also provided a report to show the warm efficiency when installing insulation materials in a space. People without professional knowledge of architecture or insulation materials can intuitively understand the effects of installing insulation materials, instead of reading the professional report and data like the R-value of specific insulation materials. Moreover, the plan comparison feature is welcome by our interviewees too. This feature can let people feel different materials' thermal performance so they can choose a more suitable solution for themselves.

VI. Next Steps

Based on the feedback, we should consider the next steps. Since our solution is an application, the most important thing for the next step is to upgrade the features of our applications. From the feedback collected from the interviewees, the price, quality, and safety of the insulation materials are of great concern to our users. Therefore, we consider providing our users with different prices and quality insulation materials. This way, users can make the best choice for their own situation. At the same time, we also provide in our report the safety of each insulation material chosen by the user. During the interview, we collected some information from professionals. They mentioned that there are a lot of elements that will significantly affect the insulation performance. For example, the water absorption of materials and dimensional stability of materials. The quantity of water a material absorbs is known as its water absorption, and it is measured as the weight of the water absorbed divided by the weight of the dry material. Due to the comparatively high thermal conductivity of water, water absorption into a material's pore structure will enhance thermal conductivity. Thermal insulation's thermal resistance will dramatically diminish if it absorbs water [16]. For a house, the roof and walls are the most likely places to be exposed to water. So, the insulation materials installed in these two places need to consider the water absorption rate of the material more. However, not all users are familiar with the water absorption of materials. The dimensional stability of a material means a material's ability to keep its original proportions in the face of temperature and humidity fluctuations. Owens Corning, a global leader in insulation, roofing, and fiberglass composite materials, provides a detailed introduction to the importance of dimensional stability for insulation materials on its website. It mentioned that the dimensional stability of the insulation material has a direct impact on insulation performance and system integrity. The insulation material may bloat, expand, shrink, and buckle as a result of poor dimensional stability. The most dangerous consequences of this behavior are unexpected insulation performance, coating or waterproofing breaches, and the thermal bridges between insulation and equipment [17]. If our model can recommend the most suitable installation location for the user according to the characteristics of different insulation materials the user will not waste time trying some unnecessary solutions.

To upgrade our application's features, we still use sprint again. Based on the several features for improvement mentioned above, what we want to achieve is very clear. To review the checklists of the sprint, the first thing we want to do is to add new features to our prototype. We will still choose *Figma* as the tool. For the price and quality of our insulation materials, what we plan to do is that when users see the 3D model of a house or apartment, they will also see lots of insulation materials below that 3D model as usual. The difference is when they tap a specific insulation material, it is linked to another page that contains a list of that insulation

material with different prices and quality. For example, if the user taps fiberglass, the application will go to another page with multiple fiberglass from different companies. Users are allowed to tap on each of them to see price and quality. After they finish a plan, the application still provides a report which includes all original contents, as well as the total price of this plan, and the safety of each insulation material in users' selection. Moreover, we will add the price and quality of the selected insulation materials as weighted parameters into our machine-learning model. Thus, we will provide a comprehensive recommendation index, which is a score in the range from 0 to 5, to our users. It will consider the warm efficiency of the plan, the price and quality of selected insulation materials, and the number of carbon emissions. When we finish the prototype and make sure there is not a bug in it, we will recruit five interviewees to do the interview again. The purpose of the interview is to get feedback on our upgraded application. What we want to know is whether users will be more satisfied with our upgraded application. In addition, we would like to find out from the interview feedback that we still have new issues that arise so that we can further improve our application.

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