OPTIMIZATION OF HEAT PUMP APPLICATIONS FOR NET-ZERO EXERGY BUILDINGS

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Abstract: Steering a change for global sustainability requires a new, rationale driven approach that provides guidance to reduce emissions and protect the environment. The Rational Exergy Management Model (REMM) provides the approach of balancing natural energy resources based on their useful work potential, or exergy. For the first time, REMM formulates the level of match in the supply and demand of exergy to broader impacts on CO_2 emissions, which becomes very important to reduce global warming. Furthermore, its new parameter effectively shows the ways to reduce CO_2 emissions that have been compounded. The application of REMM to the building sector, the largest contributor of CO_2 emissions, presents examples to think beyond the present characteristics of buildings. It also shows that heat pumps must be optimized with exergy matches in combined heat and power systems to reduce compound CO_2 emissions. It is expected that this approach will be put into practice to achieve carbon wedges from buildings and set a vision for net-zero exergy buildings. An analysis tool is also developed to support the educational purposes of the REMM model.

Key Words: ***exergy, CO_2 emissions, heat pumps, analysis tool***

1 INTRODUCTION

With the challenge of global warming being one of the greatest challenges for humanity, the need for effective measures to provide the flexibility to reduce CO_2 emissions is greater than ever. This calls for a need to evaluate the allocation of natural energy resources at large beyond measures to conserve the quantity of energy. In particular, it calls for a new, rationale driven approach that provides the guidance to rematch the supply and demand of natural energy resources based on the quality of energy as its useful work potential, or exergy. Annex 37 and 49 of the IEA also seeks to further the claims for the use of exergy (IEA 2007). The Rational Exergy Management Model (REMM) was developed to provide a new, common metric that formulates the need to balance the supply and demand of exergy to reduce CO_2 emissions (Kilkis 2007). It also formulates that the present allocation of energy resources produce CO_2 emissions that are compounded in excess, including those in heat pumps. Such an approach directly addresses the need to optimize the use of resources with exergy matches so that values as low as 0.04 may be improved toward higher visions. Therefore, the real flexibility to reduce CO_2 emissions and steer a change for global sustainability requires the ability to rematch the supply and demand of resources as formulated by REMM.

2 THE REMM MODEL

In its basic form, exergy measures the useful work potential of a given energy source based on its maximum temperature relative to the temperature of a reference environment. As a result, the amount of exergy directly depends on the temperature differential that an energy source is able to make with the reference environment. REMM develops a new parameter to measure the level at which the supply of a natural energy resource to a system is balanced with its demand based on exergy values. This parameter is the Rational Exergy Management Efficiency that is given by ψ_{Ri} as the ratio of the supply and demand of exergy to a system (*i*).

$$\psi_{Ri} = \frac{\varepsilon_{dem(i)}}{\varepsilon_{\sup(i)}} \tag{1}$$

For a building as system (*i*), the demand of exergy is defined by the interaction of the building with its environment. In the heating season, the indoor air temperature of the building, T_a will be greater than the temperature of its reference environment, or the ground temperature T_g. This results in a certain flow of heat from the building to the environment that brings the values of T_a and T_g in equilibrium. Clausius' statement of the second law of thermodynamics then implies that the only way such a building system will be able to raise the value of T_a back to its original value is with an external work input of some kind. This becomes the exergy demand of the system from an external resource in the amount of *P* as given below:

$$\varepsilon_{dem(i)} = \left(1 - \frac{T_g}{T_a}\right) \times P \tag{2}$$

In turn, the building must be supplied an energy resource that fulfills the characteristics of the exergy demand as $\varepsilon_{dem(i)}$ to satisfy Equation 2. As a result, this resource must have a value of exergy that is equal to or greater than the value of $\varepsilon_{dem(i)}$. This also requires the resource to have a maximum temperature equal to or greater than the value of T_a. If a fossil fuel is used to satisfy the exergy demand, then the maximum temperature will be defined by the value of its combustion temperature, T_f. In reference to T_g, the exergy of the supplied resource will be:

$$\varepsilon_{\sup(i)} = \left(1 - \frac{T_g}{T_f}\right) \times P \tag{3}$$

The exergy supply defined as $\varepsilon_{sup(i)}$ in Equation 3 completes the definition of the parameter ψ_{Ri} in Equation 1 for a building system (*i*). The value of ψ_{Ri} ranges from zero to one, which corresponds to the poorest and highest level of rationality in balancing the supply and demand of exergy, respectively. Higher values mean that there are better balances in the supply and demand of exergy, which is the ultimate goal. Furthermore, higher values mean that less exergy is wasted due to any mismatch in the supply and demand and hence, lessen the impact on other systems and the environment (Kilkis 2007). This aspect is based on the value of any wasted exergy, $\varepsilon_{dst(i)}$, and any resulting exergy impact on another system (*j*), $\varepsilon_{sup(j)}$.

$$\varepsilon_{\sup(j)} \geq \varepsilon_{dst\,(i)} = \varepsilon_{\sup\,(i)} \times (1 - \psi_{Ri}) \quad \text{where,} \quad \varepsilon_{dst\,(i)} = \varepsilon_{\sup\,(i)} \times (1 - \psi_{Ri}) \tag{4}$$

Equation 4 shows that the parameter ψ_{Ri} is used to quantify the exergy impact of any supply and demand mismatch in the first system (*i*), which may be the building system. In particular, a value of ψ_{Ri} less than one allows for the excess supply of resources in another system (*j*), $\varepsilon_{sup(j)}$ only to make up for the wasted exergy, $\varepsilon_{dst(i)}$. This widens the boundary of REMM as given in Figure 1 to include the simultaneous impact of a mismatch in the supply and demand of exergy beyond the first system. It provides the basis to formulate the compound impacts from a broader CO_2 emissions perspective that becomes very important to reduce global warming. It implies that emissions are now compounded and reducing them requires exergy matches.

2.1 Compound Emission Impacts

Figure 1 shows that there may already be direct CO_2 emissions due to the supply of exergy to system (i), which may be the building system. Per unit energy, P, this depends on the carbon content of the resource, c_i and the energy efficiency of the equipment that uses the resource, n_i. The value of direct CO_2 emissions does not depend on the parameter ψ_{Ri}. In general, however, the best balances in the supply and demand of exergy are possible with resources with lower values of c_i. Figure 1 also shows that there is a secondary CO_2 emissions component, which may be avoidable in part given a higher value of ψ_{Ri}. This is termed the avoidable CO_2 emissions of system (i) that take place in system (j) due to any initial mismatch in the supply and demand of exergy (Kilkis 2007). It is given by Equation 5:

$$\Delta CO_{2j} = \frac{c_j}{n_i} \times (1 - \psi_{Ri}) \tag{5}$$

The avoidable CO_2 emissions of system (i) that is given in Equation 5 as ΔCO_{2j} derives from Equation 4. Once system (i) wastes a portion of its supplied exergy as given by ψ_{Ri}, it becomes responsible for this secondary component since it could have done better to reduce or even displace these emissions. As a result, these emissions take place regardless of whether or not system (i) is actually linked to the other system (j) with value c_j. Together with any direct emissions, the responsibility of system (i) may be compounded as given by ΣCO_{2i}:

$$\Sigma CO_{2i} = CO_{2i} + \Delta CO_{2j} = \frac{c_i}{n_i} + \frac{c_j}{n_i} \times (1 - \psi_{Ri}) \tag{6}$$

Equation 6 indicates that increasing the value of the parameter ψ_{Ri} must be a prerequisite when deciding the options for a system. In fact, increasing only the value of n_i will have minor effects on reducing CO_2 emissions when compared with the compound impact of any low values of ψ_{Ri}. On the other hand, increasing the value of ψ_{Ri} may even displace the compound CO_2 emissions responsibility of system (i), ΣCO_{2i}. In this way, the parameter ψ_{Ri} becomes an effective guide when deciding on options that will have the minimum compound impacts. Figure 2 also depicts that raising the value of ψ_{Ri} will minimize the value of ΣCO_{2i}.

2.1.1 The impacts of the base case

With a building system as system (i), it becomes very important to balance the supply and demand of exergy to reduce CO_2 emissions. Currently, however, almost the entire building stock is characterized by mismatches in the supply and demand of exergy. This also applies to buildings that have very high efficiencies on the equipment level, including for heat pumps. This is mainly because the exergy of the resource that is supplied to the building is far greater than the exergy demand of the building. Per unit P and general values of T_g, T_a, and T_f as 283K, 293K, and 2000K, respectively, the value of ψ_{Ri} will be only 0.04 from Equation 1:

$$\psi_{Ri} = \frac{\varepsilon_{dem\,(i)}}{\varepsilon_{\sup\,(i)}} = \frac{0.03}{0.86} = 0.04 \tag{7}$$

The result of Equation 7 shows that the level of rationality in balancing the supply and demand of exergy in building systems is very low at a near zero value of 0.04. This also indicates that the exergy of the supplied resources is almost entirely destroyed. Such a result does not change if the fossil fuel resource was to be used in a highly efficient boiler. There will still be the mismatch with the exergy demand of the building for its heating needs. The same applies to any resource that is converted to electricity in a central power plant and used in an air-to-air heat pump at the building. The exergy mismatch will remain as above.

The base case's low value of ψ_{Ri} at 0.04 further means that it has exergy impacts on another system (*j*). This is because the wasted exergy is now being made up for elsewhere with the use of additional resources. As a result, the use of any fossil fuel for space heating will have instantaneous impacts. It will result in an avoidable impact on another system from the broader scope of the REMM boundary. The exergy impact from Equation 4 per unit *P* will be:

$$\varepsilon_{\sup(j)} \geq 0.83 = 0.86 \times (1 - 0.04) \quad (8)$$

Such an exergy impact is comparable with the additional use of resources at a central power plant to generate electricity from the same kind of resources that the building system wasted. As a result, system (*j*) may now be designated to be a central power plant that uses fossil fuels. The broader impacts of the building are also tangible once the low value of ψ_{Ri} takes place and in practice, the building does not need to receive any power from the central power plant to be responsible for its compound CO_2 emissions. This is because the building already wasted an amount of exergy that could have been used instead to generate an equal amount of electricity. Furthermore, the transmission efficiency from the central power plant, n_T, must be put to Equation 9 to fully explain the CO_2 impact of ψ_{Ri} at 0.04 within the REMM boundary:

$$\Sigma CO_{2i} = CO_{2i} + \Delta CO_{2j} = \frac{c_i}{n_i} + \frac{c_j}{n_i \times n_T} \times (1 - \psi_{Ri}) \quad \text{where,} \quad \psi_{\mathrm{Ri}} = 0.04 \quad (9)$$

For general values of n_i as 0.70, and n_T as 0.75, both the direct and avoidable CO_2 emissions within the value of ΣCO_{2i} in Equation 9 equal to 3.3×c_i per unit of energy. For natural gas, the value of c_i is 0.02 kg of CO_2 per kW·h. Clearly, the base case is responsible for far more than direct CO_2 emissions. Figure 3 further illustrates this base case where a building system receives a resource with a value of $\varepsilon_{sup(i)}$ and c_i. This resource may be used in a boiler or heat pump to meet the exergy demand of the building. However, the poor balance between the supply and demand of exergy results in a low value of ψ_{Ri} and compound CO_2 emissions as illustrated. The building stock must think beyond this base case to improve its performance.

3 OPTIMIZATION WITH REMM

Figure 3 illustrates the base case of buildings in the stock that REMM formulates to compound CO_2 emissions in proportion to its low value of ψ_{Ri} at 0.04. The broader impacts of a poor balance between the supply and demand of exergy further indicate that the base case may not be improved with only incremental changes in the values of n_i or n_T. As a result, the method of optimization within the REMM boundary is to improve the value of ψ_{Ri} by means of better balances between the values of the supply and demand of exergy. In this way, the approach of REMM also directly focuses the options for the building system into addressing the initial exergy mismatch from which the compound CO_2 emission impacts may be traced.

3.1 Alternative Cases of REMM

It is possible to optimize the exergy balance of the building system in multiple ways. One way is to optimize the exergy balance on the side of its exergy supply. This is possible given a resource with a lower exergy, such as those of waste heat or renewable energy. Another way is to optimize the exergy balance on the side of its exergy demand. This is possible given an additional exergy demand beyond space heating, such as for combined heat and power. Yet another way is to optimize the two with a lower exergy supply that meets both heat and power. This is possible given the integration of various renewable energies in the building.

For example, the balancing act of matching the supply and demand of exergy in the building system may take the structural form of district energy. Figure 4 shows that the central power plant may redirect the exergy of its resource into a closed loop system after electricity generation. This would seek to transfer the exit temperature of the resource by means of heat exchangers to the water that circulates in the closed loop to the buildings. In effect, the buildings would meet their exergy demand with a lower temperature, lower exergy resource. The value of ψ_{Ri} in the overall calculation would also be high since the exergy of the resource is used for both heat and power. In such cases, the value of ψ_{Ri} is calculated by Equation 10:

$$\psi_{Ri} = \left(1 - \frac{\varepsilon_{dst\,(\mathrm{i})}}{\varepsilon_{\sup\,(\mathrm{i})}}\right) \text{ from } \varepsilon_{dst\,(\mathrm{i})} = \varepsilon_{\sup\,(\mathrm{i})} \times (1 - \psi_{Ri}) \text{ where, } \varepsilon_{\mathrm{dst\,(i)}} = \left(1 - \frac{T_g}{T_{app}}\right) \times P \quad (10)$$

In combined heat and power (CHP) options, the amount of the exergy demand precedes any portion of the exergy supply that is wasted. This reversal is because the exergy demand for both heat and power is affected by the top temperature values of the resource from T_f down to the temperature T_{app} rather than T_a. However, since exergy is always defined relative to the temperature of a reference environment, the exergy that is wasted, or $\varepsilon_{dst(i)}$, is now in the position to be directly defined relative to T_g based on values of T_{app} and lower. This explains Equation 10, which is alternatively arranged from the condition of Equation 4 as given above.

From Equation 10, it is now possible to determine the value of ψ_{Ri} given a general value of the return temperature of the water in the closed loop as 360K for T_{app}, and 0.86 for $\varepsilon_{sup(i)}$ as already found for fossil fuels per unit P. In contrast to the base case values for the building system, Table 1 gives ψ_{Ri} to be at the much higher value of 0.75. The combined heat and power option of Figure 5 at the micro level further improves upon this value. It also uses radiant panels that are able to capture a lower temperature at 340K. As a result, the value of ψ_{Ri} for the option of Figure 5 is even higher at 0.80. While the value of ψ_{Ri} is still less than one, both eliminate the kind of compound CO_2 emissions as previously defined for the base case.

Table 1 also shows that the method of optimizing the match in the supply and demand of exergy effectively reduces CO_2 emissions relative to the base case. It shows that better balances in the supply and demand of exergy eliminate the compound CO_2 emissions of the base case, which had been in proportion to the low value of ψ_{Ri} at 0.04. The highest values of ψ_{Ri} beyond the values of 0.75 and 0.80, however, are only possible with a balancing act that requires matching the supply and demand of exergy in the building system with various renewable energies. The structural form of this option may take the form a ground source heat pump (GSHP) that is optimized to be driven by a wind turbine as depicted in Figure 6. From the perspective of the REMM boundary, its closer exergy match will give more benefits.

3.1.1 All renewable energy

The micro-CHP option of Figure 5 could have used a more environmentally friendly or renewable form of fuel while optimizing the exergy match in the supply and demand. Yet, this option would not be benefiting from the close match between the exergy demand of the building based on T_a and the ground temperature T_g that could be raised to a higher value using a GSHP. The only disadvantage of using a GSHP to meet the thermal needs of the building would be its dependence on electricity that currently comes almost entirely from central power plants. As a result, the value of ψ_{Ri} would be no different than in the base case of the building at the low value of 0.04 where now, the central power plants will be using a high exergy fossil fuel to meet basic thermal needs, which will disrupt its initial exergy match.

The boundary of REMM indicates that the initial match of the GSHP must be continued in the entire natural energy resource chain to optimize the exergy match in the supply and demand.

This will allow the GSHP to retain its initial exergy match between its ability to collect the ground source heat for the building and the building's thermal needs. This will also permit the GSHP to act within an all renewable energy resource integration that allows the overall supply and demand of the building to be rematched based on exergy. In this sense, it may also resemble the structural form of a micro-CHP. The GSHP will provide the thermal needs of the building while another resource will provide the electricity to drive its compressor and supply electricity to the building. It may be a green exergy bundle that acts as a micro-CHP.

The way to optimize the initial exergy match of GSHP in buildings is to link it with a renewable energy resource that is able to generate electricity with some of the lowest values of exergy. These may include any distributed sources of renewable energy, such as those of wind, solar, and small hydropower. Equation 11 formulates the exergy supply from these sources, which is to be optimized for the lowest temperature value that may be used to generate electricity, T_e. The value of T_e may also be found from a technique that uses the available energy to work conversions to find a temperature equivalent value. This is called exergy mapping and the value of T_e was found for the first time for wind energy (Kilkis 2007).

$$\varepsilon_{\sup(\mathrm{i})} = \left(1 - \frac{T_g}{T_e}\right) \times P \tag{11}$$

Based on the exergy mapping technique, the value of T_e for the temperature equivalency of wind energy was found to be 471K. The idea of a temperature equivalency for wind is also not distant given that wind energy is due to thermal differences in the Earth's atmosphere. In fact, renewable energy resources, such as wind energy, all have exergy values naturally although they may not be always quantified by them. In comparison to the flame temperature of fossil fuels, renewable energy resources also provide much lower temperature values when it comes to practical values that may be used on-site. As a result, the rationale driven approach of REMM is able to widen the focus from improving the performance of GSHP on the equipment level to optimizing its resource level with the use of renewable energy sources.

The structural option that optimizes the resource level of a GSHP with a renewable energy may therefore include the use of wind energy. Since this will be a green exergy bundle that acts as a micro-CHP, the value of the parameter ψ_{Ri} will be calculated based on Equation 10. Here, the value of $\varepsilon_{sup(i)}$ will be based on the value of T_e in Equation 11. The value of $\varepsilon_{dst(i)}$ will be the portion of the wind's exergy that overlaps with the GSHP's exergy supply between T_g and T_a. This is because this amount will not be used twice from both the wind resource and the GSHP that already met this requirement. In Equation 12, the value of ψ_{Ri} is found to be 0.91:

$$\psi_{Ri} = \left(1 - \frac{\varepsilon_{dst(\mathrm{i})}}{\varepsilon_{\sup(\mathrm{i})}}\right) = \left(1 - \frac{0.03}{0.40}\right) = 0.91 \tag{12}$$

The high value of ψ_{Ri} at 0.91 surpasses the values of the other options due to the match between the supply and demand of exergy that was optimized based on renewable energy. The use of the GSHP for its initial exergy match and its bundling with wind energy truly takes its place as one of the best options to provide heat and power to the building. The lessons that may be taken from this example may also be applied to other renewable energy options. This is to optimize the supply and demand of exergy with renewable energy in combined heat and power bundles, and to set a focus beyond the equipment level to the resource level. The current need to rematch energy resources is not one that is to be fixed on any other level.

If a new building is to adopt this option, it will have zero CO_2 emissions. In contrast, a building that is retrofit from the base case to this option may even have negative emissions.

Such a retrofit building will eliminate the avoidable CO_2 emissions of the base case due to a low value of the parameter ψ_{Ri}. In the building stock, this will have the effect of Equation 13:

$$-\Delta CO_{2j} = -\frac{c_j}{n_i \times n_T} \times (1-\psi_{Ri}) \tag{13}$$

The optimization of options for buildings within the REMM boundary, which indicates all of the subsequent impacts from a low value of ψ_{Ri}, shows the urgent need to retrofit buildings from the base case. This is even more important than such new buildings for their net impact on the building stock's CO_2 emissions that will otherwise continue to be compounded due to exergy mismatches. Visions for net-zero buildings also make a call to correct this situation.

4 NET-ZERO BUILDINGS

Present targets define a net-zero energy building as a building that receives no more energy than is provided by the building's on-site renewable energy sources, annually (ASHRAE 2008). This definition is useful as a starting point to move the building toward being a producer of energy. The optimization of the option to integrate GSHP and renewable energy will also clearly have a role to play in meeting this target. The green exergy bundle of the two will not require the building to receive electricity from a central power plant to drive its GSHP. Given favorable wind conditions, the building may even be able to meet or exceed its entire energy load with this option that opens the possibility of putting some of its power on the grid.

Furthermore, the rationale driven approach of REMM provides a guide to let any building optimize the balance between the supply and demand of exergy. This allows buildings to maximize the options to use the exergy of their energy resources and come closer to net-zero targets. It also indicates aspects that would make a better balance in the supply and demand of exergy that effectively optimizes combined heat and power options. Most importantly, it provides a guide to let buildings change their characteristics away from a misuse of exergy that result in compound CO_2 emissions. These are all prerequisites to reach net-zero targets.

Another net-zero target was envisioned to be a net-zero exergy building target (Kilkis 2007). A net-zero exergy building (ZEXB) is one that always engages in options with high balances in the supply and demand of exergy and minimizes any compound CO_2 emissions, not only those relative to the base case. It also manages its options in such a way that any resource, which it may receive from the power or gas grid, is equated to resources that it gives to the grid based on exergy. A net-zero energy building will not meet this target unless is aims for it. Equation 14 gives a simplified formulation of a net-zero exergy building that pursues this target:

$$\sum_{k=1}^{m} \varepsilon = \sum_{k=1}^{m} \varepsilon_f - \sum_{k=1}^{m} \varepsilon_t \qquad \text{ZEXB} \Leftrightarrow \sum_{k=1}^{m} \varepsilon = 0 \tag{14}$$

In Equation 14, the summation of ε_f over all time increments *k* will indicate the exergy that a building received from the power or gas grid per annum. The summation of ε_t over all time increments *k* will indicate the exergy that a building gave to the grid per annum. A building will be a net-zero exergy building when the value of Equation 14 gives a value of zero based on exergy. The emphasis on the word net-zero is also important because the exergy in the exchanges is eventually consumed. However, the sum of those values may still be net-zero. Hence, the target pushes buildings to consume only as much exergy from the grid as it gives. This also considers the exergy of those exchanges, which was left out of the original target.

As one possibility, the building may be a hybrid building that engages in all of the alternative options of REMM with no time increments in which it is ever a base case building (Figure 7).

Yet, to be net-zero, it must still equate any exergy that it receives from the power or gas grid with the exergy that it gives to the grid from its own micro-combined heat and power options. The option that will allow the building to make the most strides in this way will be the option of the GSHP and the wind turbine since these are renewable energy sources that it may give to the grid. According to REMM, it is also the option with the highest value of ψ_{Ri} at 0.91. As a result, any building may take this optimized result and move toward being net-zero exergy.

4.1 The REMM Analysis Tool

The approach of REMM provides principles to the building sector to rematch natural energy resources by establishing balances in the supply and demand of exergy. These principles are useful to optimize the supply and demand of exergy to reduce compound CO_2 emissions and bring buildings closer to net-zero exergy targets. These must also be put into practice to have an effect for the environment. The REMM Analysis Tool was developed to further the educational goals of the model and allow such options to be strategized (Kilkis 2008). The Tool allows inputs of relevant variables and outputs the results based on REMM. It also provides graphs to relate the balance in the supply and demand of exergy to CO_2 emissions.

Figure 8 provides one screen of the REMM Analysis Tool for the option of the GSHP and the wind turbine, which is termed all green. The graphs on the right show that this option has a close balance in the supply and demand of exergy as an option that resembles micro-CHP. This is because the GSHP receives its electricity from an on-site renewable energy source rather than a distant power plant that uses fossil fuels. This allows it to compare favorably with a high value of ψ_{Ri} at 0.91 in contrast to the base case value of ψ_{Ri} at 0.04. The graphs for CO_2 emissions also allow the Tool to calculate carbon wedges between this option and the base case. A carbon wedge is defined by a CO_2 reduction between the emissions of the base case and an alternative option. For example, a new building that implements this option using 18,000 kW·h will save 11.7 tons of CO_2 emissions each year relative to the base case.

Graph 1 as given by the Tool also shows the CO_2 reduction potential given a certain number of buildings, *B,* that may implement this option each year. This is fixed at a trend of 5% of existing buildings and 20% of new buildings that may implement this option each year. Graph 1 further shows that the next four to five year window of opportunity is very important to set this trend in motion. If successful, the CO_2 reduction from this option alone will be a carbon wedge that will lessen the annual CO_2 emissions of the year 2055 by a value of 2.6 gigatons. This potential shows the real possibilities that may be taken by moving away from incremental changes and into improvements that balance the supply and demand of exergy.

$$\omega_{REMM}(y) = \Sigma CO_{2i}(\mathrm{y})_{\text{Base Case}} - \Sigma CO_{2i}(\mathrm{y})_{\text{REMM Cases}} \times B \tag{15}$$

Equation 15 formulates the carbon wedge for the alternative options of REMM compared to the base case, ω_{REMM}. It shows that a carbon wedge in year (*y)* is possible by thinking beyond the base case and into options that improve the balance in the supply and demand of exergy with higher values of ψ_{Ri}. Equation 15 will not define a carbon wedge if the only change that the building makes is to improve the energy efficiency of its equipment, n_i, which will not alter the use of resources from the perspective of the REMM boundary. This carbon wedge reminds the need to balance the supply and demand of exergy to reduce CO_2 emissions. Clearly, the challenge of global warming will require the use of means to rematch resources.

5 CONCLUSIONS FOR GLOBAL SUSTAINABILITY

Steering a change for global sustainability requires a new, rational driven approach that provides the flexibility to reduce emissions and protect the environment. REMM formulates the means to rematch natural energy resources based on balances in the supply and demand of exergy, which effectively eliminates the compound CO_2 emissions of the base case. Furthermore, REMM guides the building sector to redefine its impacts as the largest contributor of CO_2 emissions. This is made possible with the guide of a new parameter, the Rational Exergy Management Efficiency, or ψ_{Ri}. This metric also shows the ways to optimize combined heat and power options for buildings, including those that use a GSHP with a wind turbine in resemblance to a micro-CHP. Such an alternative case provides one of the options with the highest value of ψ_{Ri} at 0.91. As a result, this option is valuable in achieving higher targets for net-zero exergy buildings and carbon wedges from the building sector, all of which will be important to reduce global warming. Options such as these further show that a flexibility to reduce CO_2 emissions already exists and merely waits to be put into practice. The REMM Analysis Tool also aids in this respect and toward reestablishing peace with Nature.

6 TABLES AND GRAPHICS

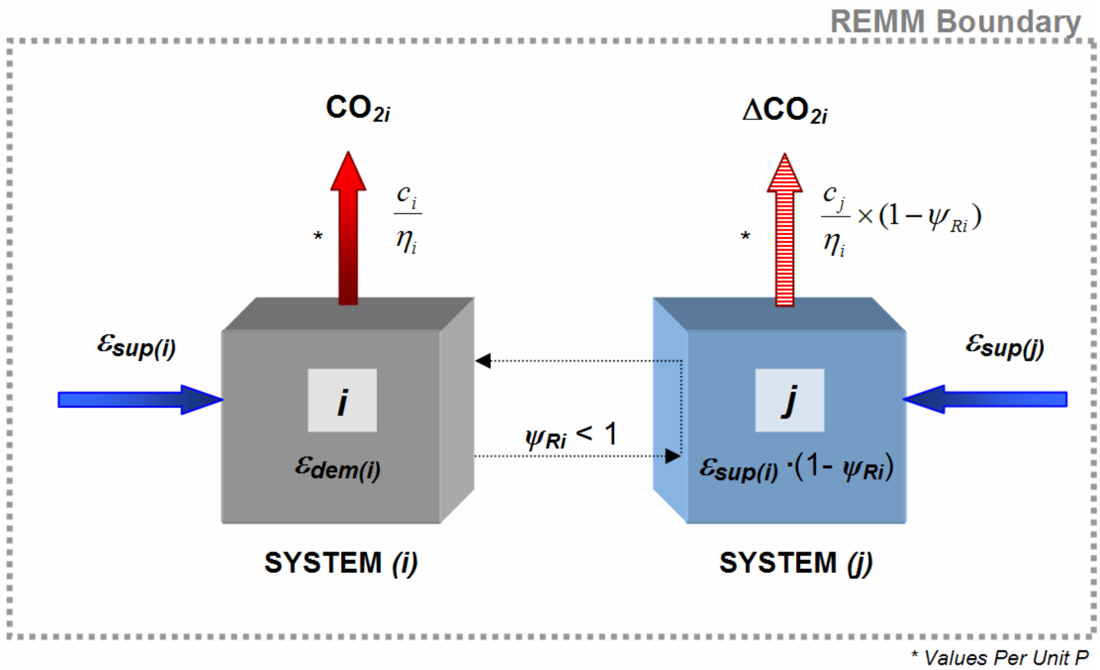


Figure 1: The REMM Boundary Based on the Parameter, ψ_{Ri}

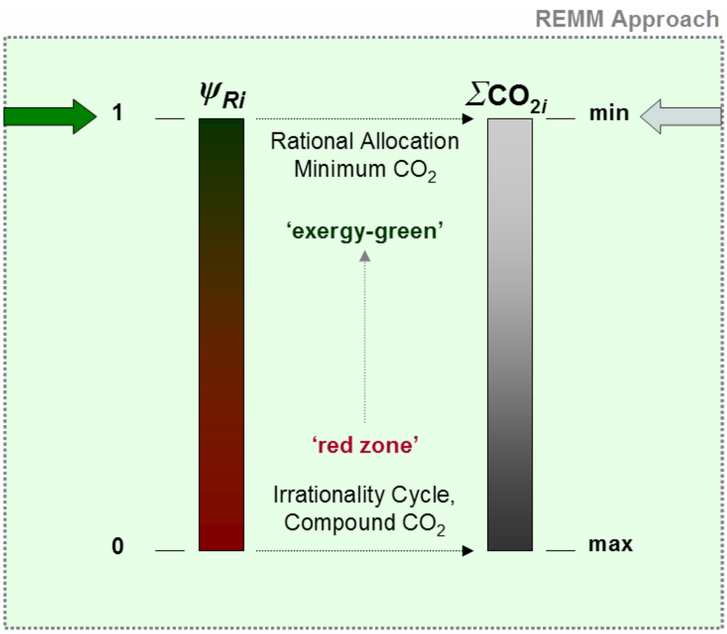


Figure 2: The Approach of REMM to Reduce Compound CO_2 Emissions

Table 1: Comparison of the Base Case and the Alternative Cases of REMM

Case	*Value of ψ_{Ri}*	*Compound Impacts?*	*CO_{2i}*	*ΔCO_{2j}*	*Value of $\sum CO_{2i}$*
Base	0.04	Yes	*x*	*x*	$3.3\times c_i$
One	0.75	No	-	*x*	$1.8\times c_i$
Two	0.80	No	*x*	-	$1.1\times c_i$
Three	0.91	No	-	-	0 or $-1.4\times c_i$

*Values Per Unit P

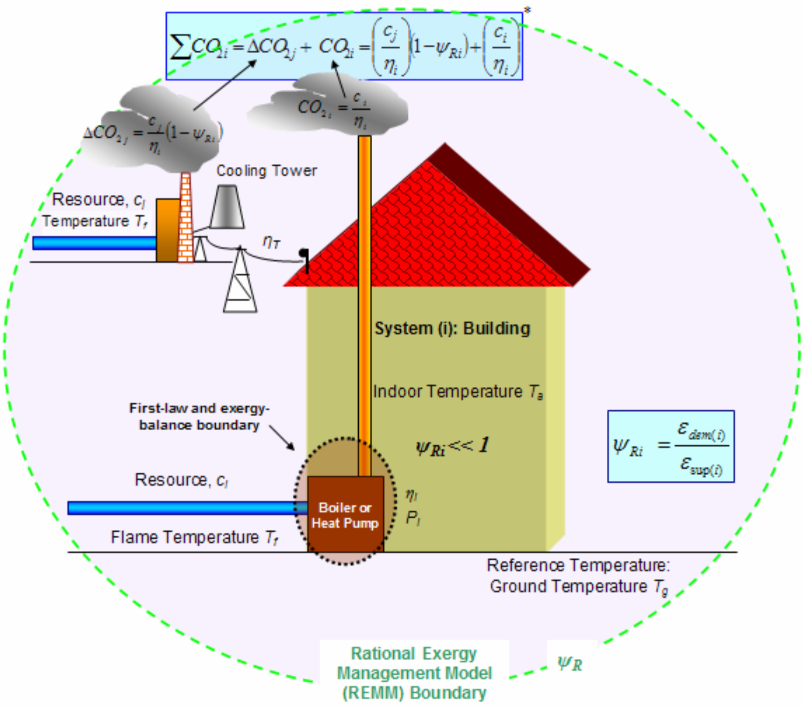


Figure 3: The Base Case of the Building Stock and the REMM Boundary

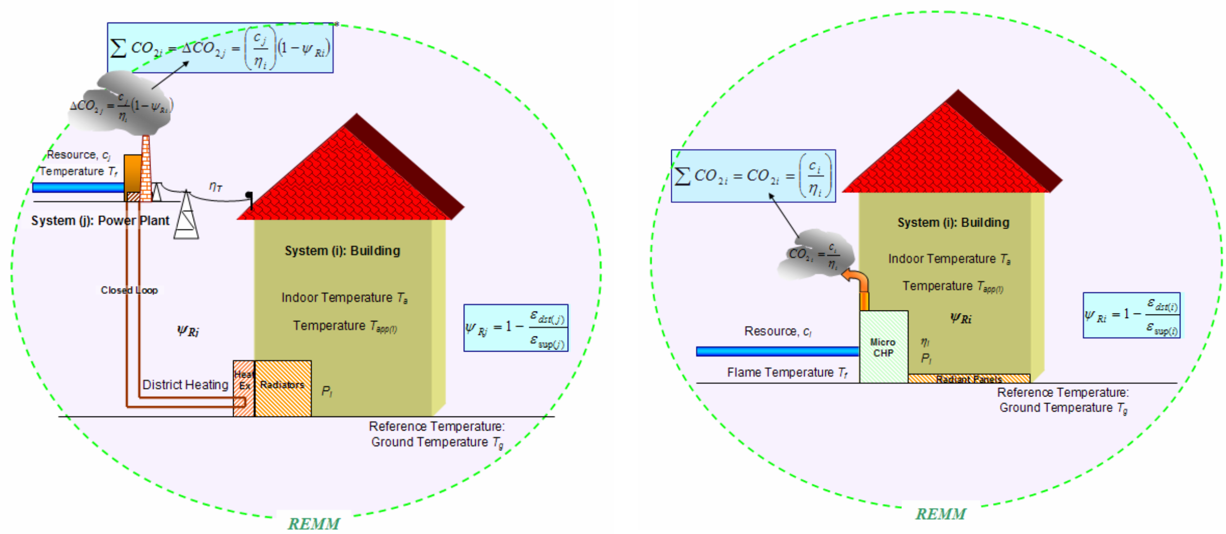
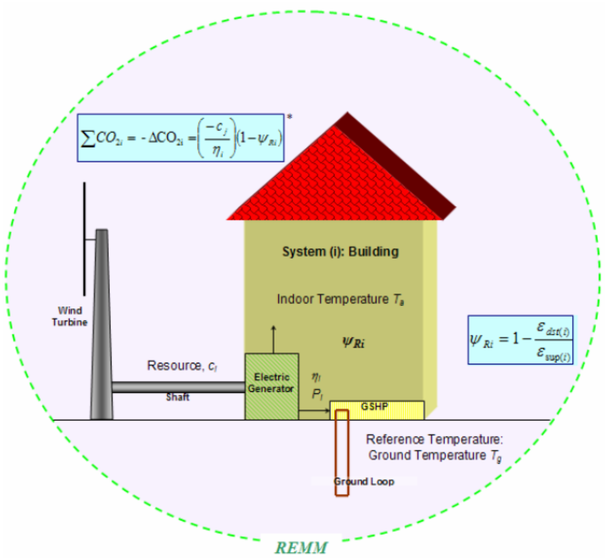


Figure 4 (Left) and 5 (Right): Two Alternative Cases of REMM



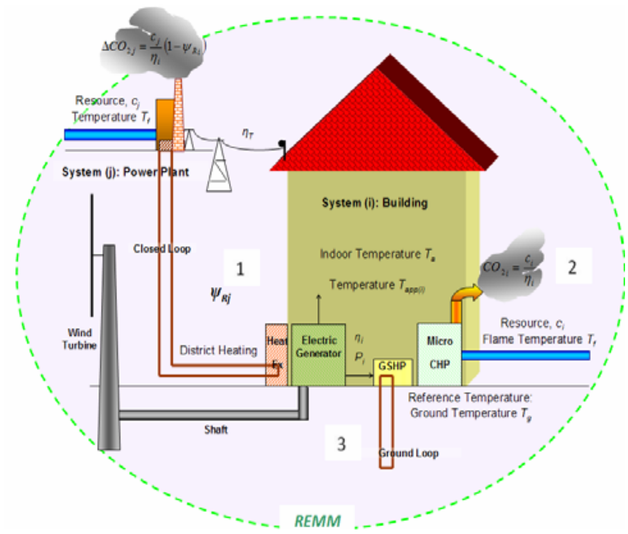


Figure 6: All Renewables Alternative (Left), Figure 7: Sample Hybrid for Net-Zero Exergy (Right)

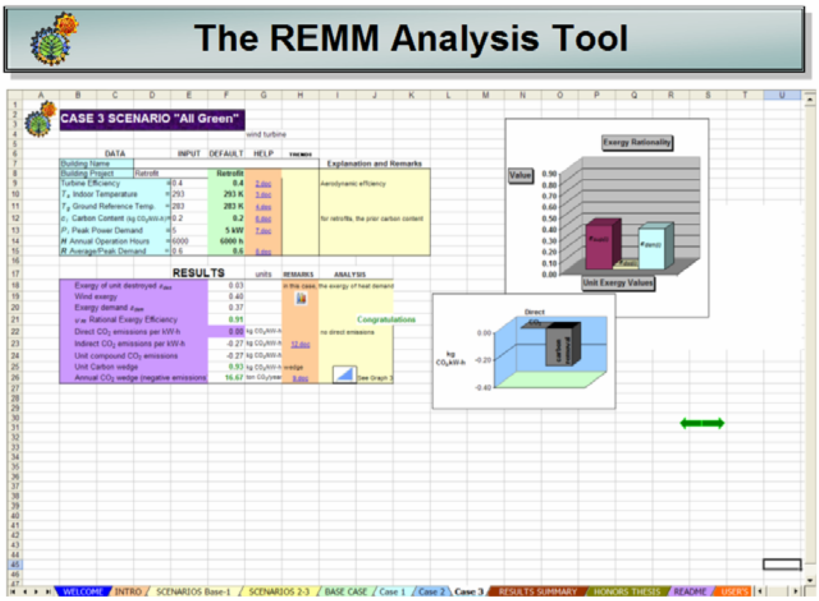


Figure 8: One Screen of the REMM Analysis Tool

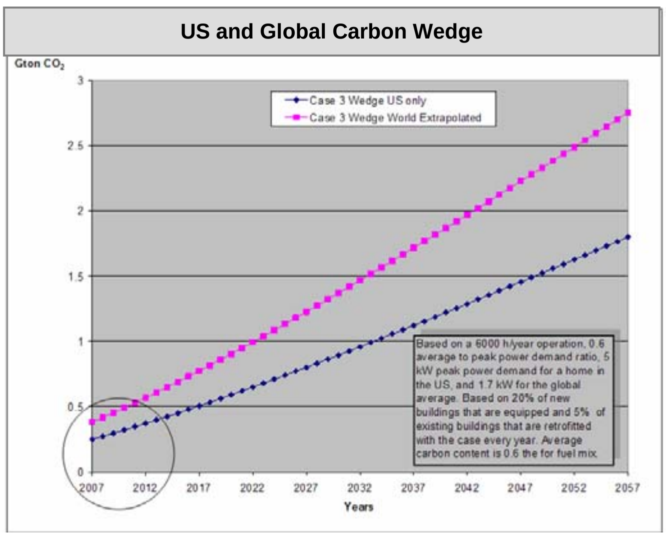


Figure 9: The Carbon Wedge Based on Equation 15

7 NOMENCLATURE

c …. Carbon Content of Resource .. kg CO_2/kW·h
CO_{2i} .. Direct CO_2 Emissions ……….. kg CO_2
k …. Unit Time Increment ……….. hour (h)
n_i …. Equipment Efficiency ………dimensionless
n_T …. Transmission Efficiency……dimensionless
P …. Energy Load …………………. kJ or kW·h
T_a …. Indoor Air Temperature …….. kelvin (K)
T_{app} .. Application Temperature …… kelvin (K)
T_e …. Optimized Temperature …….. kelvin (K)
T_f …. Combustion Temperature …... kelvin (K)
T_g …. Reference Ground Temp.…….kelvin (K)
ΔCO_{2j} Avoidable CO_2 Emissions …... kg CO_2
$\varepsilon_{dem(i)}$ .. System (i) Exergy Demand …. kJ or kW·h
$\varepsilon_{dst(i)}$ .. System (i) Exergy Destroyed .. kJ or kW·h
ε_f …... Exergy from the District ……... kJ or kW·h
$\varepsilon_{sup(i)}$ .. System (i) Exergy Supply ……. kJ or kW·h
$\varepsilon_{sup(j)}$ .. System (j) Exergy Supply ……. kJ or kW·h
ε_t …… Exergy to the District ……….. kJ or kW·h
ΣCO_{2i} .. Compound CO_2 Emissions …. kg CO_2
ω_{REMM} .. REMM Carbon Wedge ……… Gt CO_2
B …….. Number of Buildings …… dimensionless
y …….. Wedge Year Variable ….. dimensionless
ψ_{Ri} ……. Rational Exergy Management Efficiency ………. dimensionless ……..

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