OPTIMIZING LOW CO_2 SOLUTIONS WITH HEAT PUMPS TOWARDS NET-ZERO EXERGY COMMUNITIES OF THE FUTURE

Siir KILKIS, PhD Candidate, Division of Building Technology, School of Architecture and the Built Environment, The Royal Institute of Technology (KTH), Stockholm, Sweden and the Scientific and Technological Research Council of Turkey (TUBITAK), Ankara, Turkey

Abstract: Net-zero building design is a potentially transformational concept for the energy systems of today. State-of-the art in net-zero building design, however, is not without major shortcomings, which may be addressed through net-zero exergy buildings (NZEXB). This paper provides key insight into the design principles of NZEXBs based on lessons that are learned from a premier net-zero exergy "ready" building in Ankara. These include building technology integration with better exergy matches in a multi-path approach and diversified thermal energy storage as a buffer between the supply and demand of exergy to reduce CO_2 emission impacts. Modeled data indicate that the building will attain "net" self-sufficiency with an annual exergy consumption of 60 kWh/m^2-yr and proposed renewable exergy supply of 62 kWh/m^2-yr. The building further has a 75% savings in compound CO_2 emission impacts over a baseline building. The results indicate that NZEXBs are the "building blocks" for the more exergy-aware energy value chains of tomorrow. The strategies that were utilized at the building level are thus applicable to being scaled-up to higher levels in the energy system. The paper concludes with key strategies for the net-zero exergy communities of the future.

Key Words: net-zero, exergy, buildings, CO_2 mitigation

1 INTRODUCTION TO STATE-OF-THE-ART IN "NET-ZERO" DESIGN

Net-zero buildings represent a paradigm shift in the energy and exergy value chain. In contrast to mainstream buildings, net-zero buildings are not only much lower end-users but are also actively positioned throughout multiple chains of the value chain itself. Based on the smart integration of low energy, sustainable construction techniques with renewable energy production, net-zero targets can transform buildings to expand horizontally within the value chain, i.e. into the production, conversion, storage, and transmission of energy (**Figure 1**).

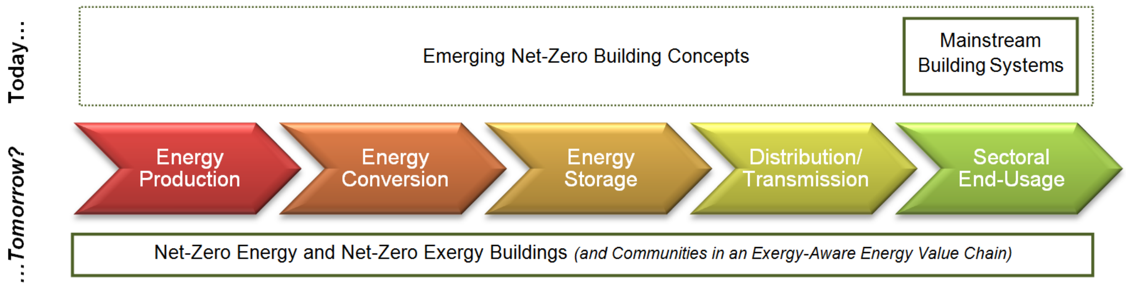

Figure 1. The Repositioning of Building Systems within the Energy/Exergy Value Chain

As the presently dominant concept in "net-zero" building design, net-zero energy buildings (NZEB) are commonly taken as buildings that receive no more energy from the grid than is provided back to the grid from the buildings' on-site renewable energy sources, annually. However, there is yet to be a single, universal definition for NZEBs due to boundary issues, e.g. site vs. source energy (Torcellini 2006). In the search for the best concept, the metric of the balance, the balancing period, the type of energy use, accepted renewable energy options, and building-grid interaction are also among the differences between definitions

(Marszal et al. 2011). The Recast of the Energy Performance of Buildings Directive further provides a general “near” net-zero energy building definition, which implies that a very low amount of energy usage is to be covered mostly by renewable energy sources (2010/31/EU).

As an original survey of state-of-the-art in net-zero building design, **Figure 2** maps out the relative positioning of net-zero and “near” net-zero energy buildings based on the respective values of renewable energy supply (x-axis) and total energy usage (y-axis) in kWh per meter square, annually. In the middle of the graph area, the 45-degree line represents the condition where the value of the renewable energy supply is equal to the total energy usage on an annual basis, which may be used as a reference to differentiate between net-zero and “near” net-zero energy buildings as its lower and upper-bound areas, respectively. Other than those buildings that are on the reference line having exactly a “net-zero” energy status, the deviations away from the line in both directions roughly indicate the level of net energy usage (for “near” NZEBs) or net-energy production status (exceeding NZEB) as further indicated.

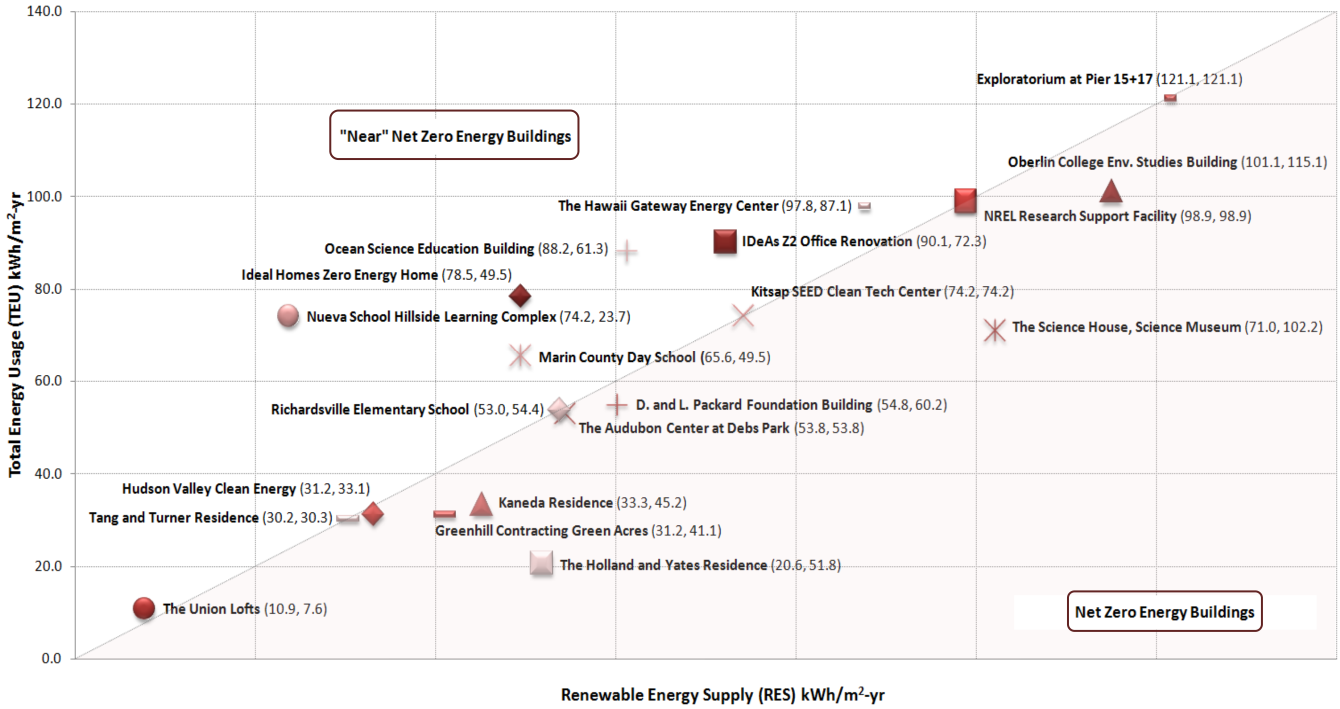

Figure 2. Positioning of Net-Zero and “Near” Net-Zero Energy Buildings (based on axes RES vs. TEU)

Coming to or exceeding the NZEB definition depends on a multitude of factors, such as site and climatic conditions, renewable energy potential, the selection of renewable and energy technologies, and building construction characteristics. These factors, which must all be carefully addressed in being able to balance the renewable energy supply and the total energy usage towards coming to any net-zero targets, are also an important part of the reason behind the diverse span of values in Figure 2. Based on an original compilation of data from available sources, the buildings that are referred to in Figure 2 are each marked by various characteristics within five main comparative domains as discussed in (Kilkis 2010).

The state-of-the-art of net-zero and “near” net-zero energy building design, however, is not without some major shortcomings. These shortcomings are essential to more effectively bring “near” net-zero buildings closer to net-zero targets and shift net-zero buildings in Figure 2 rightward into also being “net” energy producers. For example, a building that qualifies as net-zero energy may still be using electricity and natural gas for space heating, space cooling, and domestic hot water not only in cases of backup, but also as part of the regularly planned building design. Solar electricity may further be allocated by default to HVAC and domestic hot water needs. In addition, NZEBs are more close to being net-zero “electricity” than truly net-zero energy, which would also include any thermal exchanges. The metric of NZEBs, however, are indifferent to low exergy resources, such as district energy systems (more common in Europe), CHP, and thermal storage. Due to metric issues as well as lack of vital design guidance, NZEBs come short to address these missing areas of improvement.

2 THE NEXT STEP: NET-ZERO "EXERGY" BUILDINGS FOR THE FUTURE

Being closer to net-zero "electricity" than net-zero energy parallels the fact that the metric of the quantity of energy in NZEBs is indifferent to thermal varieties. By default, this places a de-emphasis on the better utilization of thermal energy sources both within and outside the building, e.g. micro-CHP, thermal energy storage, and district energy systems. It also makes it difficult to diversify the way in which the supply and demand of both electricity and thermal energy is matched on-site at the building while leaving missing areas of improvement in net-zero design. The state-of-the-art may further illustrate these missing areas of improvement:

• **Scenario 1**: A "near" net-zero energy building that uses gas-fired boilers to provide radiant, in-floor hydronic heating and then buying an extra grid-supplied renewable electrical energy.
• **Scenario 2**: A net-zero energy building that provides radiant heating based on "high-efficiency" condensing boilers while using a bay-water heat exchanger for radiant cooling.
• **Scenario 3**: Net-zero energy buildings that directly allocate solar electricity for split system HVAC and domestic hot water or supply hot water through use of a woodchip biomass boiler.
• **Scenario 4**: A net-energy "producing" building that directly allocates electricity for electric heating from its on-site PV or the electricity grid while "eliminating" the use of natural gas.

Scenarios 1-4 are from real cases that have come near, already achieved or even surpassed the NZEB target. If the same scenarios are approached from a perspective that not only considers the quantity of energy but also its "quality" as a measure of the useful work potential of energy, however, stark mismatches remain in the design decisions to allocate energy sources to demands. Addressing these areas of improvement will affect performance, curb CO_2 emission impacts, and in this way, enhance state-of-the-art net-zero building design.

Exergy is a measure of the useful work potential of a given amount of energy based on a Carnot cycle that is defined according to the temperature difference with a reference environment. It is a key aspect in differentiating, diversifying, and matching thermal varieties in energy loads. According to the Rational Exergy Management Model (REMM), the level of match in the supply and demand of exergy is further indicative of any CO_2 emissions that are being compounded in the energy system (Kilkis 2007-a). A net-zero exergy building (NZEXB) is thus originally termed by the author as "a building that has a total annual sum of zero exergy transfer across the building-district boundary in a district energy system, during all electric and any other energy transfer that is taking place in a certain period of time (Kilkis 2007-b). IEA Annex 52 on "Towards Net Zero Energy Solar Buildings" also acknowledges NZEXBs as net-zero buildings that consider "both the quantity and quality of energy" (Napolitano 2010).

In view of Scenarios 1-4 that characterize state-of-the-art net-zero buildings, there is a lack of design principles to recognize the presence of different "exergy" demands within a building (low exergy for space heating and cooling and high exergy for electricity, etc.). Consequently, the allocation of high exergy resources to the undifferentiated energy demands in buildings does not seem to present an area for objection in present net-zero energy building design. In contrast, however, a REMM based approach for net-zero exergy building design brings to the forefront the need of addressing any poor exergy matches to improve net-zero performance.

As a means of comparison, in NZEXB design, diversifying the demands and matching them with sources of supply based on exergy stands as a key principle. This provides additionality to basic NZEB principles, namely managing the net-zero status of the building by reducing energy loads, e.g. building construction and passive solar design, and producing energy on-site. This addition principle, which was missing in Scenarios 1-4, allows the building designer to distinguish the demands that could not be differentiated by the quantity of energy alone. In this way, the designer is to adopt an approach that seeks to match the exergy demands with a wider array of supply options to maximize the parameter ψ_{Ri} as a measure of the level of exergy rationality (Kilkis 2008). Therefore, while recognizing the low exergy demand of space heating and cooling, the designer is to adopt a “multi-path” approach to match the demand and supply sides. The load reduction and the management of the “net-zero” status is further to be made considering both energy and exergy aspects, such as the decision to import low exergy resources and opt for low exergy options on-site. **Figure 3** depicts the key principles.

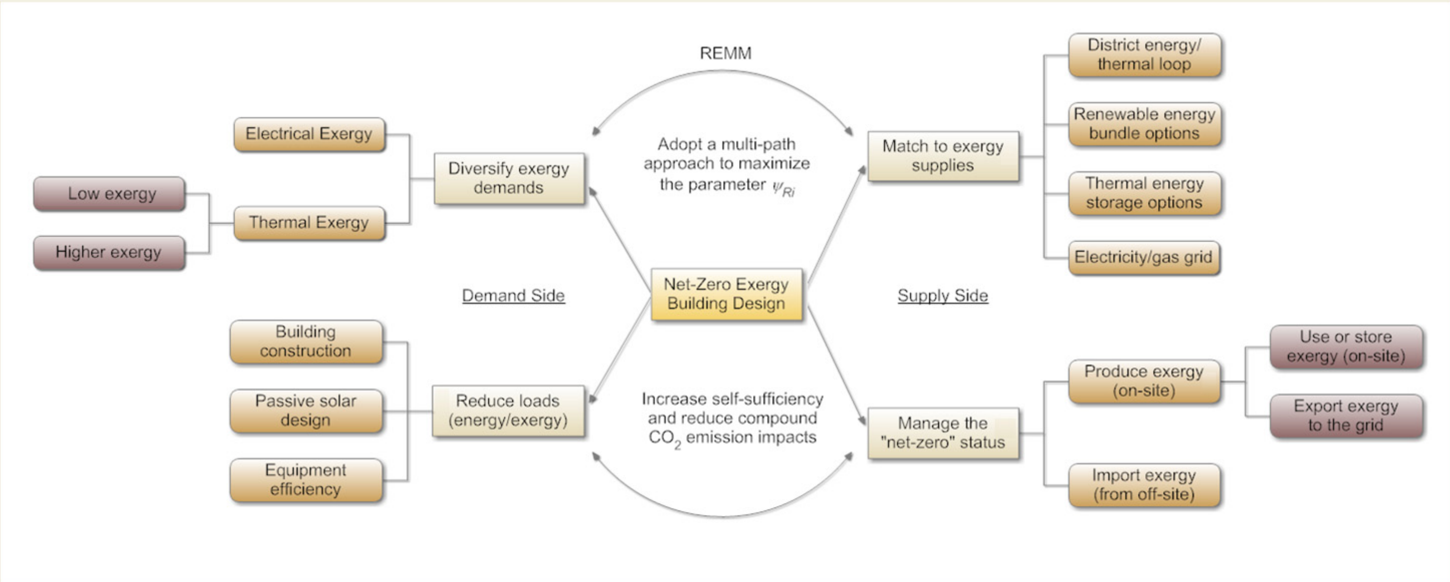

Figure 3. Key NZEXB design principles to manage the demand (left) and supply sides (right)

Within NZEXB design, another added-value of REMM is to allow for an increase in “net” self-sufficiency and to reduce compound CO_2 emissions impacts. REMM emphasizes the need to consider a rationale in which the level of exergy mismatches represents broader impacts in the energy system, including CO_2 emissions. This rationale is particularly fitting for NZEXB design as the interaction of buildings with the grid is taken into account based on exergy. Here, REMM contributes by an analytical perspective where the level of exergy mismatch in a building system greatly affects the need of that system to engage in an extra usage of resources as imported energy from the grid or to forgo chances to export its own generated energy to the grid, all of which affect its net-zero status. Thus, the internal management of exergy based on REMM is “key” to improve the more external net-zero status of the building.

2.1 Extended Formulations in Support of NZEXB Design Principles

Currently, there is no equation to explicitly express the status of being “net-zero.” This leaves ambiguity on whether total energy usage (TEU) and renewable energy supply (RES) or the import and export of energy commodities (energy and/or exergy) is to be used in the balance for net-zero. From a wholesome view, however, these can be seen to be all connected. **Eq.1** quantitatively expresses the ultimate condition that must be managed to determine the net-zero status of the building based on exergy. The annual exergy consumption (AEXC) in Eq. 1 is formulated based on three terms, the exergy that is imported from the grid (first term as ε_{fg}) plus the exergy that is produced on-site (second term ε_{on}) minus the exergy that is exported to the grid (third term ε_{to}), all as the summation of their values over the course of one year:

$$AEXC = \Sigma\varepsilon_{fg} + (\Sigma\varepsilon_{on} - \Sigma\varepsilon_{to}) \quad (1)$$

Re-arranging Eq.1 provides a statement that is better fitted to determine the net-zero status of a NZEXB. AEXC minus ε_{on}, which represents the “net” self-sufficiency of the building to meet its annual exergy consumption from on-site production, is equal to the difference between ε_{fg} and ε_{to} (**Eq.2**). This holds true because at any given time in a year, any AEXC that is not met by on-site generation results in an import of exergy from the grid and vice versa, i.e. any on-site generation that will exceed AEXC at that time results in an export of exergy to the grid. Depending on whether the status of a building has neared, achieved or surpassed the NZEXB target, the annual sum in Eq.2 accounts for the variances in all of such instances, including those when peak production may not line-up to times of peak demand.

$$AEXC - \Sigma\varepsilon_{on} = \Sigma\varepsilon_{fg} - \Sigma\varepsilon_{to} \tag{2}$$

The NZEXB status may also be reached by meeting all of the AEXC from on-site production in real-time. Being on an annual basis, however, a NZEXB interacts with the energy system as necessary. A NZEXB, for example, has the flexibility of importing exergy from the grid today and exporting exergy to the grid tomorrow while managing its overall net-zero exergy status. The main checkpoint is the conditionality of “if and only if” the annual sum of ε_{fg} minus ε_{to} is less than or equal to zero. This condition will hold true for a building that has reached or surpassed the NZEXB target but not for a building that may have only neared this target.

Table 1 provides the “toolkit” of dedicated metrics for a building level decision-maker to apply NZEXB design principles. **Eqs. 3-5** define them mathematically while their symbols are given in the nomenclature section. This toolbox further supports the guidance depicted in Figure 3.

Table 1. A Decision-Makers “Toolkit” of Dedicated Metrics for Appling NZEXB Design Principles

	Design Principle	Supporting Guidance	Dedicated Metric	Eq.
Toolbox	**Adopt a multi-path approach**	*Maximizing the parameter ψ_{Ri} requires diversifying the exergy demands (low exergy, etc.) to better match them with exergy supplies, through use of TES, etc.*	$\psi_{Ri} = \frac{\varepsilon_{dem(i)}}{\varepsilon_{\sup(i)}}$ *(poorest) 0 < ψ_{Ri} < 1 (highest)*	(3)
	Increase “net” self-sufficiency	*Managing the net-zero status based on exchanges of exergy reduces the import of high exergy from the grid to be more self-sufficient towards the NZEXB target.*	$NZEXB \Leftrightarrow \Sigma\varepsilon_{fg} - \Sigma\varepsilon_{to} \leq 0$	(4)
	Curb compound CO_2 emissions	*Better exergy matches improves the overall external relations of the building, i.e. less compound CO_2 emissions in the energy system and better net-zero status.*	$\Sigma CO_{2i} = \left(\frac{c_i}{\eta_i} + \left(\frac{c_j}{\eta_j} \times (1-\psi_{Ri})\right)\right) \times P_i$	(5)

3 LESSONS FROM A NET-ZERO EXERGY READY BUILDING IMPLEMENTATION

A premier case towards realizing NZEXB design comes from a new commercial building in the capital city of Ankara, Turkey (the ESER Green Building). As of February 14, 2011, the building has been awarded the first Platinum rating in Turkey by the Leadership in Energy and Environmental Design (LEED). Currently, the building, which has 6,971 square meters of conditioned floor space, is also a NZEXB “ready” building. While it has not yet reached the NZEXB target, its integration of building technologies based on exergy matches provide a robust background with which to meet the NZEXB target once the on-site renewable energy systems are fully scaled-up. Its “exergy-aware” characteristics may be highlighted as follows:

- The demands are diversified based on exergy, which provides a sufficient basis to match them to a more diverse array of exergy supplies, i.e. a multi-path approach for exergy matches. At the same time, thermal energy storage (TES) is utilized as an interface to facilitate these matches and to allow the exergy matches to meet in time as necessary.
- Parallel with the exergy demands, the TES tanks themselves are diversified into “low exergy” and “higher-low exergy” tanks. This further provides a “circular exergy” approach that does not allow the exergy output from any system to be destroyed but stored either as is or after being upgraded. Thus, the exergy from a system is harvested for future use.

- On the exergy supply side, building technology is integrated in multi-system bundles that are each activated and de-activated to optimally fill the area below the hourly exergy demand curves. The bundles that run at the base load also feed the TES tanks for peak load shaving during the day, which allows building technology to be sized more optimally.
- The multi-system bundles are integrated to maximize the value of the parameter ψ_{Ri} and reduce the building's compound CO_2 emissions in the energy system based on REMM.

3.1 A Multi-Path Approach of Matching Diversified Exergy Matches

Figure 4 illustrates the way in which the diversified exergy demands are matched to their counterpart exergy supplies. Here, as a NZEXB "ready" building, the design is integrated such that when the design is mapped out into the matrix of Figure 4, the multi-path approach is seen to be used in directing high exergy supplies (top left area) to high exergy demands (top right area). The same approach is used to direct low exergy supplies (bottom left area) to low exergy demands (bottom right area). In this way, lower exergy supplies are directed to diversified low exergy demands, i.e. radiant heating and cooling, domestic hot water, and higher low temperature heating and cooling. Hence, there are horizontal rather than crisscrossing linkages across the supply and demand sides that effectively minimize exergy mismatches as seen in the state-of-the art (Scenarios 1-4) and maximize the parameter ψ_{Ri}.

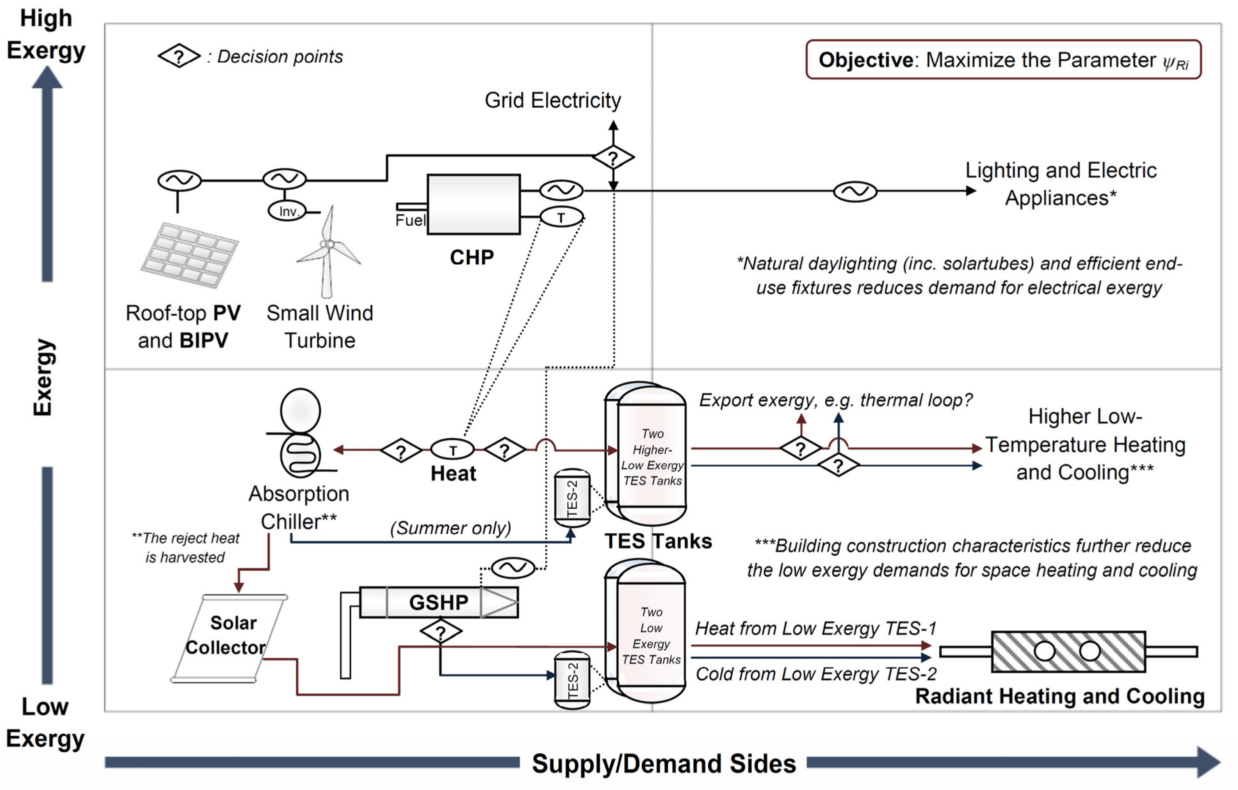

Figure 4. Matrix Layout of the Diversified Exergy Matches within the NZEXB "Ready" Building Design

Here, the CHP runs at an optimum 24-hour base load. The heat of the CHP is directed to the "higher-low exergy" TES tank (≈368 K) and the electricity to any power demands. Part of the electricity from the CHP and/or renewable energy as available is also directed to drive the GSHP (*COP*=3) that provides heat to the "low exergy" TES tank (≈338 K). This low exergy TES tank is further fed from the solar thermal collectors, which may be assisted by reclaimed heat from the absorption chillers. The roof-top PV, building integrated PV, and the low velocity sensitive wind turbine are used directly for power demands. Any electricity from the CHP and/or PV and wind turbine that exceeds the building's electricity loads is exported to the grid. Between the supply and demand sides, the "low exergy" and "higher-low exergy" TES tanks stand as an interfacing buffer, which allow the supply and demand of exergy to meet in time. The demand side includes low and higher low-temperature heating and cooling.

As a whole, Figure 4 indicates the integration of heat pumps with low CO_2 building solutions. In the future, when the on-site renewable energy systems are scaled-up, including biogas based on local greywater for the CHP unit, the on-site production from renewables will be increased to allow the building to transform its NZEXB "ready" status into NZEXB. Currently, the piping to export higher-low exergy heat and cold to a public sports arena nearby has further been completed, which will allow the building to function as a local energy satellite in the community. The NZEXB "ready" building has thus created its own opportunities to share its benefits with the local community. Yet the export of lower exergy resources to the local thermal loop is only one of the local benefits of the NZEXB "ready" building. An educational, hands-on park that introduces renewable energy to youth is now also opened in the garden.

3.2 Modeled Data of the Baseline and Present Cases and Compound CO_2 Savings

The NZEXB "ready" building deployed many novel concepts with which to exemplify the key design principles of NZEXB. Such a NZEXB "ready" building design, however, could not be conceptualized if its integrated building design team did not consider those designs that were "beyond the horizon" of present building simulation programs. Mainstream programs, such as Energy Plus V6.0 and its interfaces, including the eQuest Building Simulation Tool (Hirsh 2010), provide several drawbacks that may limit the creativity of considering such innovative designs. First, based on the NZEXB "ready" building, the programs were limited in their "built-in" capabilities to simulate some key features. These include bundles that integrate building technology in parallel and series, TES, and micro-CHP. Rather, these programs are suited to more easily simulate building designs with singular units or less-integrated systems. Second, there was limited accessibility to simulate the way that the building design is to be activated in the time dimension to optimally fit diversified demand curves. In addition, these programs allow no input based on exergy or net-zero targets. These three major drawbacks indicate that the tools of today come short to expand the horizon of the NZEXB designs of tomorrow.

The same applies to building performance metrics, including LEED, which awarded points to the ESER Green Building under the "innovation in design" category. As part of Appendix G of the LEED application, the building was modelled for 8760 hours of the year in EnergyPlus by a third-party (Altensis 2010). The data that was made available for this research work include the baseline electricity demand and the cooling and heating loads of the building. The energy savings are reported to be about 45% and 50% for electricity and HVAC loads from ASHRAE 90.1, respectively. Taking the hourly data, side calculations were made in Excel by the author for monthly data (energy and exergy),[1] annual compound CO_2 emissions based on REMM, and other NZEXB indicators. Based on the "toolkit" provided in Table 1, monthly compound CO_2 emissions are calculated from Eq. 5 [2] and summed into an annual value.

Figure 5 provides the results for the compound CO_2 emissions of the baseline and the present NZEXB ready building. Here, a baseline building at ASHRAE 90.1 is taken to represent what is considered as "base case" scenarios with poor values of the parameter ψ_{Ri}, namely 0.34 for electricity and 0.04 for heating and cooling. In the present case, these are 0.80 for electricity and 0.79 for heating and cooling considering weighted cases of mini-CHP and renewable energy bundles with GSHP.[3] Accordingly, Figure 5 indicates a compound

[1] The energy usage of the baseline as averaged for different angled orientation is calculated to be 182 kWh per m^2 per year, which would correspond to a rating of "C2" in the Building Energy Rating (BER) scheme. The electricity energy curve is about steady through the year with the caveat that one third of the energy load of space cooling (provided as separate data) is subtracted from it considering the use of a heat pump. The space heating load is a typical "U" shape with peaks in cooler months as partly reflected in Figure 5.

[2] Here, energy loads, P_i are multiplied by a compound CO_2 emissions factor, ΣCO_{2i} which depends on the value of the parameter ψ_{Ri}, average energy efficiency of the equipment, η_i and the CO_2 content of the resource, c. The latter may further be distinguished by the value of c_i for the resource that is used on-site and its average value in the energy system, c_j as broader CO_2 emission impacts are considered in REMM.

[3] The value of the parameter ψ_{Ri} is weighted by the loads of each case in the building. These include unit ψ_{Ri} values of 0.80 for CHP, 0.91 for the RE-GSHP bundle, and 0.57 for solar collectors (Kilkis 2007; Kilkis

CO_2 emissions reduction of 75.36% over the baseline. This is a combined effect of energy load reductions, increases in the parameter ψ_{Ri}, an increase in energy efficiency by 0.10 points from an average of 0.70 to 0.80, and lower c_i for on-site resources with a mix of biogas (forthcoming), some amounts of solar and wind, and grid-purchased green electricity as 0.16 kg CO_2/kWh rather than 0.23 kg CO_2/kWh (natural gas). Between the two cases, the average value of c_j for the CO_2 content of the energy mix of Ankara is unchanged at 0.23 kg CO_2/kWh.

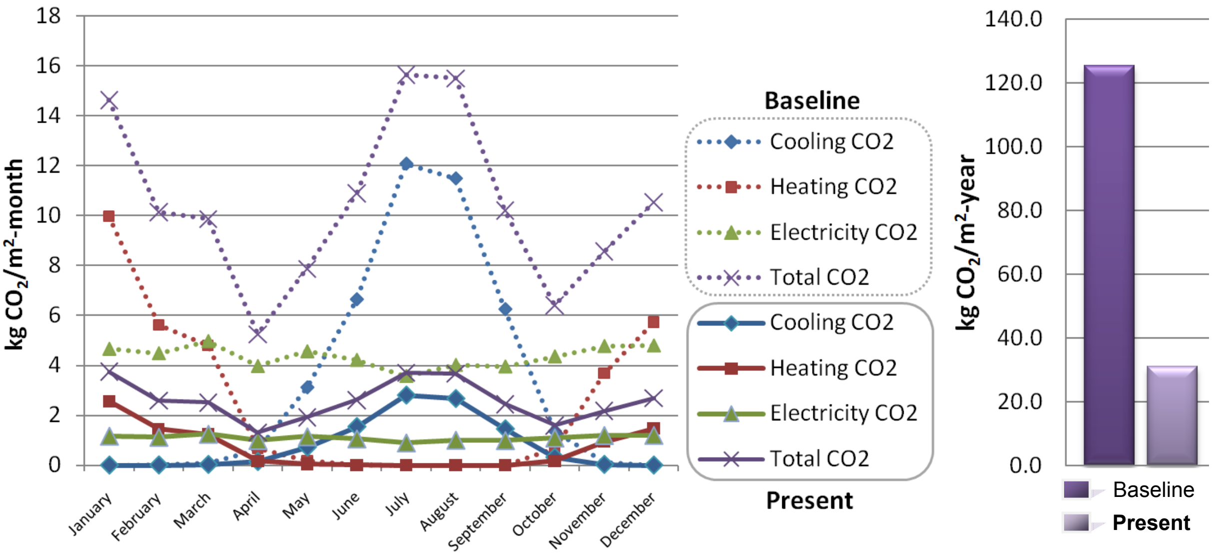

Figure 5. Monthly (left) and Annual (right) Compound CO_2 Emissions of the Modelled Building Cases

In another aspect, in the BER rating scheme, the worst values in the CO_2 emissions indicator are given to be over 120 kg of CO_2 per m^2 per year. The baseline, with its allocation of high exergy resources for low exergy demands of space heating and cooling already exceeds this amount when the avoidable CO_2 emission impacts that the overshoot of exergy has in the energy system are considered as the second term of Eq.5. Therefore, a baseline building with 182.96 kWh/m^2-year of energy usage (that corresponds to a "C2" rating, see Footnote 1) already exceeds the worst CO_2 emissions value when this is considered as compound CO_2 emissions, which is found to be 125.85 kg of CO_2 per m^2 per year. In contrast, those of the present case are 31.01 kg of CO_2 per m^2 per year (Figure 5). This situation indicates that vital CO_2 emission benefits may largely remain hidden in BER unless the boundary to assess CO_2 impacts are not extended to the energy system at large as made possible through REMM. The REMM boundary also necessitates attention to each of the target areas in Eq. 5 (Kilkis 2010). In turn, it requires that decision-making is directed into addressing all the target areas.

3.3 Outcomes of a Net-Zero Exergy "Ready" Status and Increased Self-Sufficiency

Figure 4 had already depicted the NZEXB "ready" design that integrates building technology with the aim of putting forth diversified exergy matches. Based on Figure 4, the columns of **Table 2** represent the sources of electricity production and the sources that serve the higher-low exergy and lower low exergy TES as buffers to meet space heating and cooling loads. While based on hourly data inputs from the simulated model, these annual data sets per each supply point of energy *and* exergy are further supported with side calculations in Excel by the author. Here, the supplies from PV/BIPV, solar collectors, and the small wind turbine with a very low speed wind cut-off are functions of the solar radiation and wind speed at the location of the building, respectively. The CHP, which has a power to heat ratio of 79%, is a function of the hourly electricity curve while further maintaining a base-load performance to store sufficient thermal energy to meet such demands throughout the day. While it currently

2010), which are weighted by their energy loads in Table 2. In times of any instantaneous deficits to meet AEXC from on-site production, green certified electricity is purchased from the grid and/or a backup boiler is engaged (only 1.12 kWh/m^2-yr). As a whole, the mean of the value of the parameter ψ_{Ri} is found to be 0.79.

runs on the natural gas grid, its supply from locally produced biogas is a proposed project. In Table 2, the position of the CHP in the net-zero status is calculated from this latter scenario. The GSHP, in contrast, is a function of the hourly demand curve for space heating or cooling.[4]

Furthermore in Table 2, the *rows* are organized into the annual total of the energy and exergy that is produced on-site, the load of the building, and net-zero exergy status of the building. For the values under the TES column, the data is provided both as energy and exergy values. This is due to the fact that exergy values of thermal energy supplies vary according to the temperature difference that is made with a reference environment. For simplicity, the average annual values are taken for the TES tanks to differentiate the exergetic differences of the tanks. The exergy values of electric energy, on the other hand, is taken equal to any energy values by common convention since it is considered to be useful work in its entirety. While calculations are not provided in the paper, detailed explanations are further provided in Footnote 5.[5] An important bottom-line is that by summing the exergy loads in Table 2, the AEXC of the building is found to be 59.98 kWh/m^2-yr while it produces 62.37 kWh/m^2-yr on-site. From Eq.2, this provides a NZEXB status to the building based on a net exergy value of minus 2.39 kWh/m^2-yr. By further breaking down this net value to its constituents, the NZEXB "ready" building imports 2.31 kWh/m^2-yr of net electric exergy and exports 4.70 kWh/m^2-yr of thermal exergy from renewable energy sources provided that it scales-up to use biogas. The building has also made an agreement to import green, renewable energy-based electricity.

Table 2. Analysis of the NZEXB Status of the Building Implementation based on Modelled Data

NZEXB "Ready" Building	**Electricity** (Annual Total kWh/m^2-yr)			**Thermal Energy Storage (TES)** (Annual Total kWh/m^2-yr)			
				Higher Low Exergy TES Tank	Lower Low Exergy TES Tank		
	PV	**Wind Turbine**	**Combined Heat and Power (CHP)**		**GSHP**	**Solar Collectors**	**PVT**
Produced On-Site:	0.82	0.41	48.30	61.01 (Energy)	14.75	7.73	3.87
	44.62*			61.01 (Energy)	22.49 (Energy)**		
				14.09 (Exergy)* **	**3.66 (Exergy)*** **		
Load of Building	46.93 *AEXC*			61.38 (Energy)			
				13.05 (Exergy)****			
Net-Zero Status	**+2.31** (Net import from the grid)			**-4.70** (Exergy) (Net export to the grid)			

Based on Table 2, the results of the NZEXB "ready" building indicate that the building has effectively increased its "net" self-sufficiency. Annually, those instances in which on-site production may be lower than AEXC are normalized with others in which it may be greater than AEXC. In fact, it has surpassed net self-sufficiency given that on an annual basis, the value of REXS, which is equal to 62.37 kWh/m^2-yr, is greater than AEXC at 59.98 kWh/m^2-yr. Based on Eq.4, the values of the export and import of exergy (in absolute values) further reaffirms the NZEXB status. **Figure 6** thus positions the annual status of the NZEXB "ready" building in the context of the two respective axes with REXS as the x-axis and AEXC as the

[4] The demand curve for the GSHP decreases in the summer due to the dominance of a (higher) low exergy supply from the absorption chillers that are based on the heat output of the CHP, which increases slightly.
[5] In Table 2, the electricity to drive the GSHP (with *COP* 3) is subtracted from the electricity that is produced from the CHP or renewable energy bundles to indicate the amount that is available to meet plug loads and lighting based electricity loads (*). The total of the thermal energy that is produced on-site does not yet include the contribution of the PVT, which is forthcoming to utilize the existing heat from the PV to also increase its efficiency (**). Currently, the annual heating and cooling load of the building is less than that which is produced on-site. Thus, the PVT is feasible when the district thermal loop is expanded in the future and/or the GSHP is used less. In the value of the thermal exergy that is produced on-site, the energy value that is provided in the upper cell is multiplied by a quality factor that is based on a Carnot cycle as defined between the reference ground temperature at 283K and average temperature values of the TES tanks (***). In converting the thermal energy load value of the building, the weight of the higher low exergy to lower low exergy was defined according to the proportion of the energy being produced, namely 73% and 27% (****).

y-axis. Based on these axes, Figure 6 is divided into four "zones" with the main boundary being the line where REXS is equal to AEXC that runs through the middle of the graph area. The NZEXB status is attained beginning with Zone 3, which further corresponds to the case where the annual sum of $\Sigma\varepsilon_{to}$ is greater than $\Sigma\varepsilon_{fg}$ based on Eqs. 2 and 4. On the other hand, the area in Zone 2 indicates the status of a "near" NZEXB and to a much lesser extent, possibly Zone 1 in which this time, $\Sigma\varepsilon_{fg}$ is far greater than $\Sigma\varepsilon_{to}$. This is in complete opposite of Zone 4 in which the NZEXB target is greatly surpassed. It is evident in Figure 6 that the NZEXB "ready" building is positioned within Zone 3. Furthermore, as indicated by the inset of this figure, it has reached this position through applying NZEXB design principles, namely maximizing the value of the parameter ψ_{Ri} to minimize compound CO_2 emissions, ΣCO_{2i}. In this way, Figure 6 represents the use of all of the dedicated metrics in the decision-makers "toolkit" to apply NZEXB design principles (Table 1). As an original conclusion, Figure 6 is proposed as a labelling scheme to approach NZEXBs while providing key design guidance.[6]

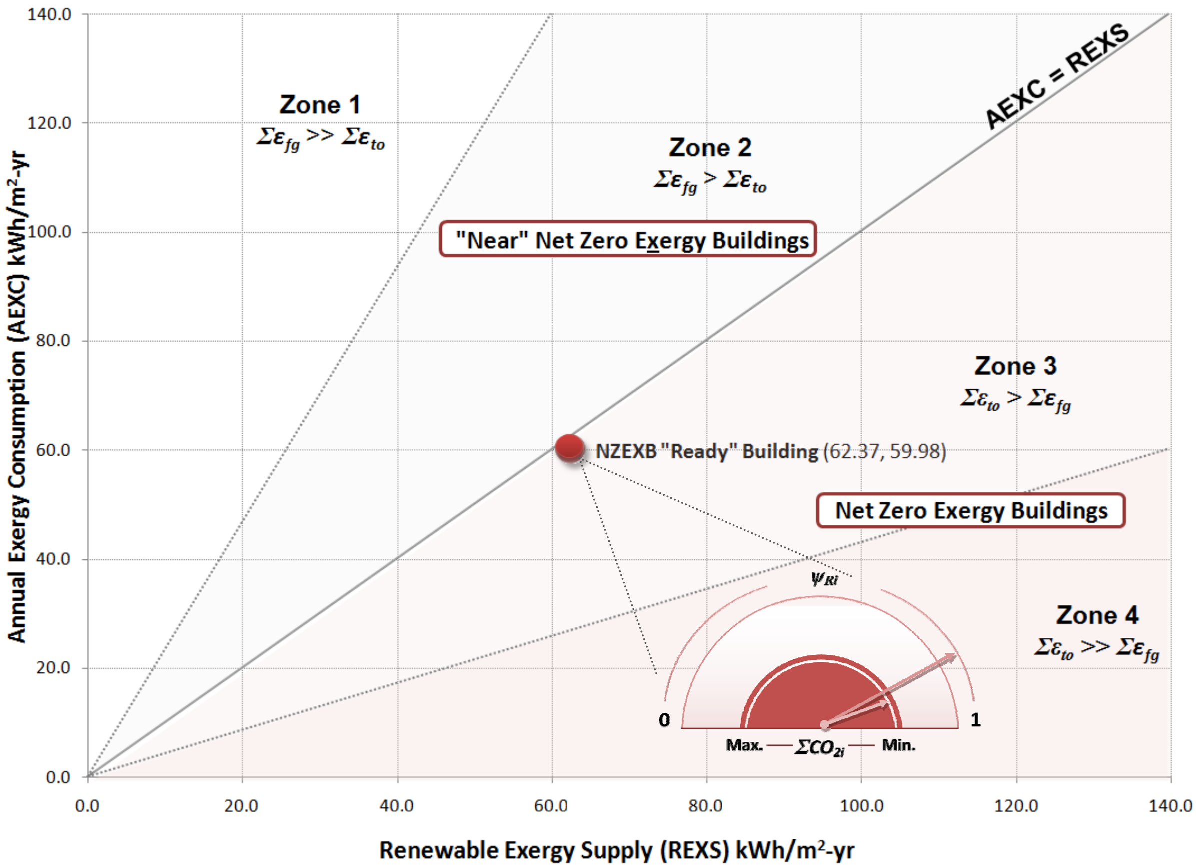

Figure 6. Proposed Scheme for NZEXBs with Axes REXS and AEXC and Design Principles (Inset)

4 EXTENDED REFLECTIONS TOWARDS NET-ZERO EXERGY COMMUNITIES

The NZEXB ready building in Ankara, which is designed as a premier case that attempts the NZEXB target based on NZEXB metrics, exemplifies a "building block" for an exergy-aware energy system. By considering REMM in the design stage, it engages in a series of exergy-aware relations to convert, store, distribute, and/or use energy for diversified exergy demands (Figure 1). In particular, it is able to do so through a multi-path approach for exergy

[6] Building labels, e.g. BREEAM, LEED and CASBEE are based on indices that are tied to energy usage, indoor air quality, and other aspects. Those for the community level are also starting to be piloted or being proposed. While varying in scope and purpose (Haapio and Vittaniemi 2008), there is no indication, however, of "net-zero" aspects in "level three" environmental assessment frameworks and rating systems. Figure 6 would be a novel contribution to building labelling schemes as well as to the state-of-the-art of net-zero design principles. Presently, a layout with the x-y axes of primary energy savings and credits has been conceptualized for net-zero energy buildings only (Heinze and Voss 2009). The layout of Figure 6 on the basis of NZEXB provides a new approach, zonal positioning, and guidance for key NZEXB design principles.

matches, i.e. the allocation of lower exergy resources to lower exergy demands, and vice versa. As much as its internal exergy matches, the building is also conscience of benefiting the local community. With respect to the global environment at large, it benefits the global climate through savings in compound CO_2 emissions, i.e. 75% over a baseline building at ASHRAE 90.1. In the context of national energy policy debates, the building further puts forth an analytical shift. It exemplifies the possibility of being an "active" producer of energy while utilizing the useful work potential of energy as exergy in rational and exergy-aware relations. All of these aspects are applicable to any unit of application anywhere around the world to contribute in putting our common future towards a more sustainable pathway. In particular, it is also applicable as a "building block" for clusters of buildings and energy systems at large.

Currently, there is an array of energy models to simulate scales beyond the building level, i.e. the community and national level, and even global building stock aggregation. Most of these energy tools are diversified by the regions they analyze, the technologies that they consider, and the objectives that they fulfill (Connolly et al. 2010).[7] None of these tools, however, are programmed for "net-zero" targets, let along net-zero exergy targets and design principles. Based on the lessons that are learned from the NZEXB ready building and its design principles, it is possible to conceptualize a new tool that is centered on the target of making a community a 100% renewable energy, net-zero exergy community (NZEXC). In a NZEXC, energy relations are knit in such a way that its linkages with local energy sources (solar, wind, geothermal, biomass, etc.) are characterized by high levels of exergy rationality (Kilkis 2010-e). A NZEXC requires principles similar to NZEXB to be applied at the community level:

Table 3. A Decision-Makers "Toolkit" of Dedicated Metrics for Appling NZEXC Planning Principles

Design Principle		Supporting Guidance	Dedicated Metric	Eq.
Toolbox: NZEXC	**Adopt a multi-path approach**	*The mean value of the parameter ψ_{Ri} is to be maximized for the area, which requires diversifying the exergy demands to better match them to exergy supplies.*	$\overline{\psi}_{R_i} = \frac{\overline{\varepsilon}_{dem(i)}}{\overline{\varepsilon}_{\sup(i)}}$ *(poorest) 0 < ψ_{Ri} < 1 (highest)*	(6)
	Increase "net" self-sufficiency	*Managing the net-zero status based on exchanges of exergy reduces the import of high exergy from the grid to be more self-sufficient towards the NZEXC target.*	$NZEXC \Leftrightarrow \sum \varepsilon_{fg} - \sum \varepsilon_{to} \leq 0$	(7)
	Curb compound CO_2 emissions	*Better exergy matches improves the external relations of the community, i.e. less compound CO_2 emissions in the energy system and better net-zero status.*	$\Sigma CO_{2i} = \left(\frac{\overline{c}_i}{\overline{\eta}_i} + \left(\frac{\overline{c}_j}{\overline{\eta}_j} \times (1-\overline{\psi}_{Ri})\right)\right) \times \Sigma P_i$	(8)

Community energy management (Jaccard et al. 1997) and the integration of measures in urban energy systems to reduce CO_2 emissions (Yamaguchi 2007) have been previously proposed. Here, NZEXCs are put forth with a completely new target for management at the community level. Just as design principles are put forth for NEXBs at the building level (Figure 3), NZEXCs require a multi-path approach to raise linkages to better exergy matches, increase self-sufficiency, and curb CO_2 emissions, now with multiple supply and demand points. In this respect, **Table 3** re-arranges the decision-makers "toolkit" for NZEXC planning principles, which requires either real-time sums or mean values of the inputs in **Eqs. 6-8**.

Furthermore, the matrix layout of the diversified exergy matches in Figure 4 is applicable to NZEXCs provided that the integration and sources of energy technology is expanded across various options at the community level. TES is also still a valid option with several municipal

[7] Some programs are well-fit for single-building, local community or other stand-alone applications. Others, such as EnergyPlan, Mesap PlaNet, INFORSE, and LEAP, have also previously simulated 100% renewable energy systems. On the other hand, the REMM Analysis Tool as developed by the author considers raising the level of exergy rationality to reduce CO_2 emissions from buildings. A tool that considers the NZEXC target would further model ways to optimize multi-path approaches for exergy matches in the community.

CHP-based district energy systems in Europe utilizing thermal energy storage, e.g. Växjö. Pilot projects, such as district loops based on solar energy with built-in TES options are another aspect. On the supply side, provided that renewable energy options are scaled-up as in the NZEXB case study, a 100% renewable energy community that is linked to exergy matches is within reach. On the demand side, these linkages can be made to high and low exergy demands in an intra-sectoral approach, i.e. electricity for public transport in addition to plug loads and electricity, and low exergy for district heating and/or cooling cascaded down to even other demands, e.g. those is agriculture. In these exergy matches, low CO_2 solutions with heat pumps have a vital role. Hence, a core emphasis in NZEXC as in NZEXB is the emphasis that a community can take steps to be "net" self-sufficient through the smart integration of linkages to exergy matches, a sample of which is given in **Figure 7**. It also emphasizes a restructuring such that built environments are not only end-users but also active producers in the more exergy-aware energy and exergy value chains of tomorrow. This is a key aspect for modeling energy and exergy strategies towards a sustainable future.

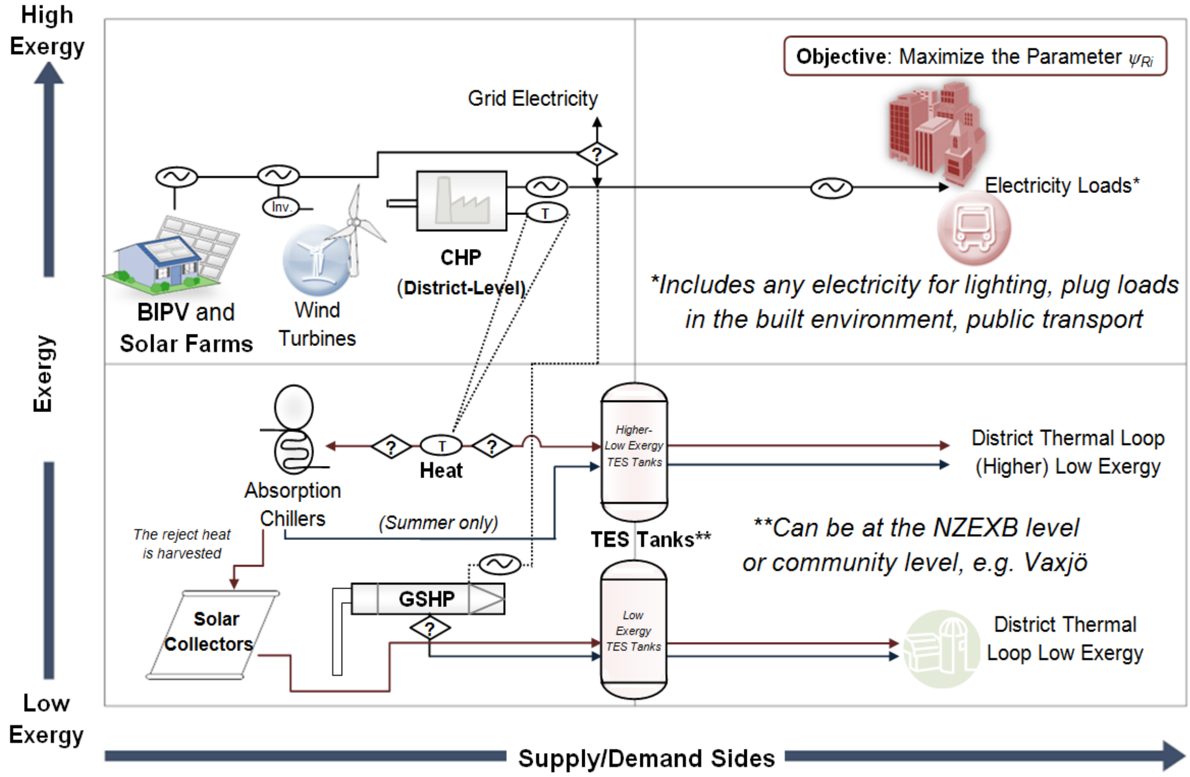

Figure 7. Sample Matrix Layout for a NZEXC based on Lessons for an Exergy-Aware Value Chain

5 CONCLUSIONS

Net-zero targets require buildings to have an active role in multiple chains of the value chain that lead to energy services. This paper has put forth the original targets of NZEXB and NZEXC to turn missing areas of improvement in net-zero design into opportunities for an exergy-aware energy value chain. In this regard, a toolkit of key design principles for these original targets provide the basis to engage in a series of exergy-aware relations to convert, store, distribute, and/or use energy for diversified exergy demands. A premier NZEXB ready building that deployed these principles as analyzed for the first time in this paper has already exemplified an innovative case that was further recognized by the LEED rating system. This includes the integration of building technology, including heat pumps, with better exergy matches and diversified options of TES as a buffer between the supply and demand of exergy. The building also provides a robust reference point to benchmark future NZEXBs and the scale-up its best practices to higher levels in the energy system as the NZEXC target. In conclusion, NZEXB and NZEXC are key concepts for the built environments of the future.

6 NOMENCLATURE

The symbols that are used in the equations of this paper are provided in the Table below:

	AEXC	Annual Exergy Consumption		P_i	Energy loads (building or community)
*	c_i	CO_2 content of the resource (on-site)	*	ψ_{Ri}	Parameter ψ_{Ri}
	ΣCO_{2i}	Compound CO_2 emissions factor		NZEXB	Net-zero exergy building
	$\Sigma\varepsilon_{on}$	Exergy that is produced on-site		REMM	Rational Exergy Management Model
	$\Sigma\varepsilon_{fg}$	Exergy that is imported from the grid		REXS	Renewable exergy supply
	$\Sigma\varepsilon_{to}$	Exergy that is exported to the grid	*	ε_{sup}	Supply of exergy
*	η_i	Energy efficiency of the equipment	*	ε_{dem}	Demand of exergy

*Their values may be provided as averages for a given community boundary as indicated in Table 3.

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