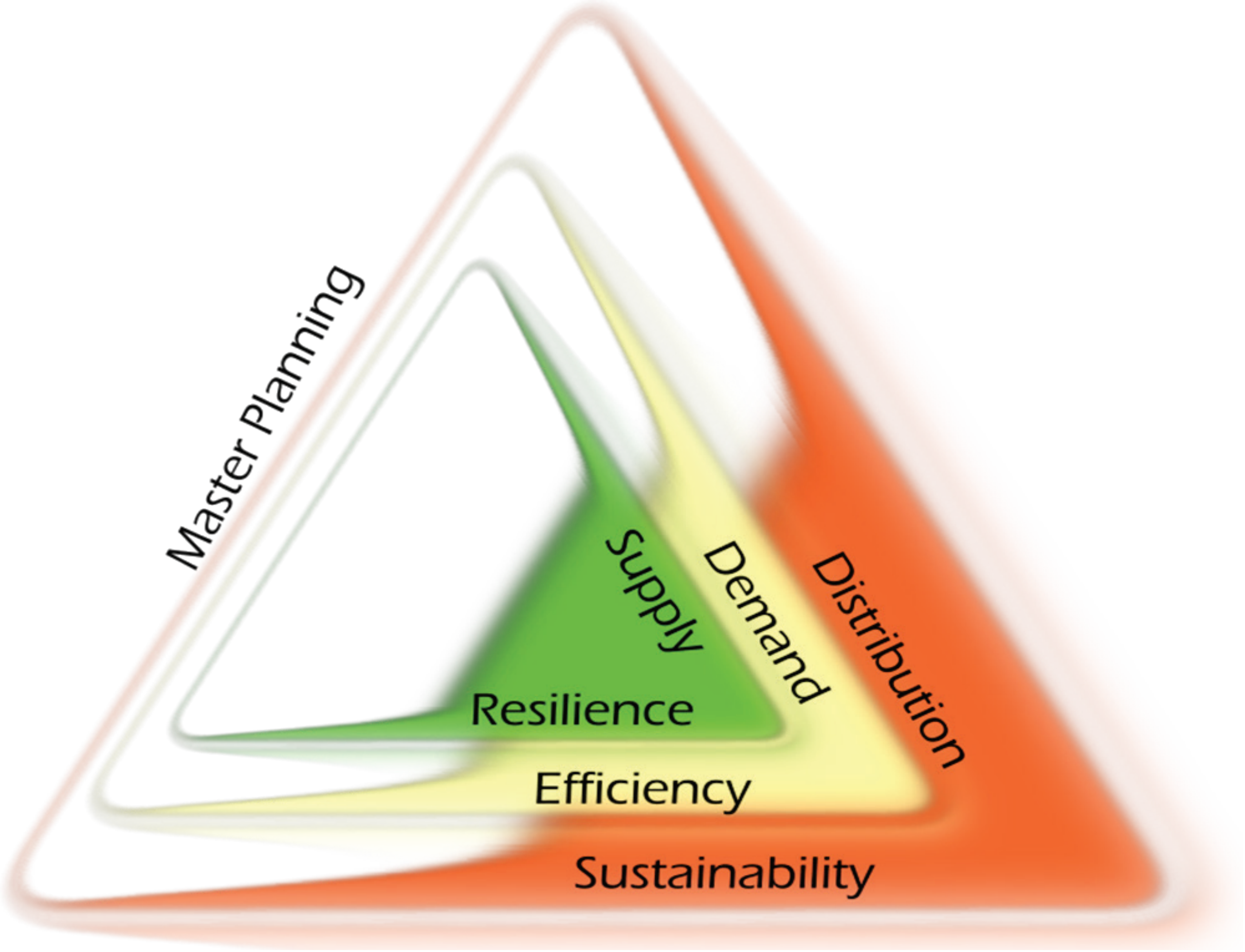
International Energy Agency

Energy Master Planning for Net-Zero Energy Resilient Public Communities (Annex 73)

Project Summary Report

October 2021



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International Energy Agency

Energy Master Planning for Net-Zero Energy Resilient Public Communities Guide (Annex 73)

Project Summary Report

October 2021

Edited by
Alexander Zhivov

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Project Summary

Buildings use about 40% of global energy, 25% of global water, and 40% of global resources; moreover, they generate approximately one-third of all greenhouse gas (GHG) emissions. Yet, buildings also offer the greatest potential for achieving significant GHG emission reductions, at least cost, in developed and developing countries. Furthermore, energy consumption in buildings can be reduced by 30 to 80% using proven and commercially available technologies [1]. Different international, national, regional, local, and institutional sustainability development goals are aiming at using affordable, low carbon, clean energy provided by resilient energy systems. Achieving these goals on the national or even on a large city level with involvement of numerous users and stakeholders, requires significant investments and coordination efforts. Nevertheless, experience of public communities that have one owner (including Ministries of Defense, universities, and hospital campuses) where all buildings and the energy system are managed using one cost center, can serve as a model for larger and more complex communities.

Until recently, most planners of public communities in the United States and in several other countries have addressed energy systems for new facilities or for major renovation on an individual facility basis without consideration of community-wide goals with regard to energy sources, renewables, storage, or future energy generation needs. Because building retrofits of public buildings typically do not address energy needs beyond the minimum code requirements, it can be difficult if not impossible to achieve community-level targets on a building-by-building basis. In today's resource-constrained environment, public communities are looking for creative ways to drive additional efficiencies in energy use and reduce associated costs. For example, a synergistic approach to diversified building cluster portfolio would allow for the storage and further use of a wide range of energy streams that would otherwise be wasted. Large, coordinated efforts are needed to establish the needed synergy between different energy initiatives and future planned projects to minimize energy use and costs.

Building-centric planning also falls short of delivering community-level resilience. For example, many building code requirements focus on hardening buildings to withstand specific threats, but a multi-building community may contain only a few mission-critical buildings that require such hardening. Furthermore, hardening is only one aspect of resilience. Recovery and adaptation should also be considered as effective energy resilience solutions. Over the past two decades, the frequency and duration of regional power outages from weather, manmade events, and aging infrastructure have increased. Major disruptions of electric and thermal energy have degraded critical mission capabilities and have caused significant economic impacts at military installations. There is a need to develop a highly resilient "backbone" of energy systems to maintain effective critical mission and service operations during such extended power outages over a range of emerging scenarios.

Best practices from around the world have proven that holistic Energy Master Planning can be the key to identifying cost-effective solutions of energy systems that depend on the climate zone, density of energy users and the local resources.

The Annex 73 goal was to develop guidelines and tools that support planning of Net-Zero Energy Resilient Public Communities and that are easy to understand and execute with the following objectives:

- Collect, analyze, and document information about best practice community-wide energy master planning processes and find out how they can be improved
- Develop energy, cost and resilience targets and constraints
- Develop a database of power and thermal energy generation, distribution and storage technologies and system architectures
- Develop guidance for energy master planning for Net-Zero Energy Resilient Public Communities
- Collect and describe business and financial aspects and legal requirements and constraints that can be used for implementation of energy master plans for public communities in participating countries
- Integrate the targets, constraints, enhanced system architectures the technology database, and resilience analysis into an interactive modeling and optimization tool

One part of the project was to collect and investigate case studies of community energy master planning. The goal of research was to investigate how energy master planning for entire communities is performed, and to find out how it can be improved. Thirty-two case studies of community master planning for military camps, universities, research institutes, hospitals, small communities, towns, and large cities have been chosen in participating countries, studied, and analyzed. In most of these cases, the buildings and systems under investigation were publicly owned. These studies have been documented and published in the Case Studies Book [IEA EBC Annex 73 2021], which includes detailed information on the drivers, the goals and the methods used for planning, implementation, and financing, and on the obtained results and lessons learned by the project owners.

The Annex 73 also investigated and analyzed framing goals and constraints for building and community energy projects that must be considered when energy master planning is conducted. They cover energy use, emissions, sustainability, resilience, regulations and directives, regional and local limitations such as available energy types, local conditions, costs of energy supply to the community and stakeholders and individual project requirements. An example of such goal is achieving resilient, low energy use communities and low-cost energy supply for the community and stakeholders.

Resilience of the energy system is one of the most important goals used for selection and design of energy systems that impacts the primary function of military installations, hospitals, and education campuses during disruptions. A variety of energy system options can be used to supply power, heating, and cooling to campuses; these options vary by the architectures and technologies used, and by whether they apply to individual buildings, building clusters, campuses, or even entire communities. Design and evaluation of system resilience measures should be based on requirements established by mission operators. As a part of research conducted under Annex 73, the framework for such requirements has been developed.

The quantitative approach to resilience established by the project team and described in the Energy Master Planning toward Net-Zero Energy Resilient Public Communities Guide (Guide) allows for evaluation of both the ability of a system to absorb the impact of a disruption (robustness), and its ability to recover.

A list of power and thermal energy system architectures technologies and technologies they employ was generated by the Annex 73 team from case studies, best practices collected using surveys conducted in the USA and in Europe from district energy associations, discussions at the ASHRAE Technical Committee (TC) 7.6 “Public Buildings” working group meetings in 2018 and 2019, and from previous experience and research conducted by the Annex 73 team members. These system architectures and technologies have been categorized and documented with their characteristics (cost and performance), application, pros and cons described. Obtained information can be used for further detailed analysis of the energy master plan baseline and of different alternatives including the Base Case and more advanced concepts to be considered in new development (“greenfield”) and/or renovation/extension (“brownfield”) projects. Different system options can be considered on the building level, building cluster level or a community level. Selection of these alternatives should consider the existing status of these systems, the goals and objectives of the project, including improvement in systems resilience, local constraints, and economic and non-economic co-benefits.

The scope of the Energy Master Plan (EMP) can be broad; it may include new construction, demolition, and consolidation projects; energy supply; and energy distribution and energy storage components, including creative methods to build innovative site-to-grid arrangements that may provide grid stability or site resilience. An EMP is not limited to energy-related projects; it may include a spectrum of non-energy-related projects, including new building construction and demolition, utility modernization projects and non-energy-related measures to enhance the resilience of energy systems to Design-Basis Threats, such as the elevation of energy equipment, construction of flood walls, burying of cables. The Guide offers variety of implementation strategies introduces methodology for LCCA of different EMP alternatives.

The Energy Master Planning concept developed by the project team and described in the Guide differs from previously developed concepts [2, 3, 8] in such a way, that in addition to meeting community’s framing energy goals, it integrates development of a highly resilient “backbone” of energy systems that allow communities to maintain critical missions and service operations effectively during extended outages over a range of emergency scenarios, whether caused by weather, manmade events or aging infrastructure.

The Energy Resilience of Interacting Networks (ERIN) tool has been developed to support an energy master planning process that allows for the assessment of the resilience of energy supply systems to various Design-Basis Threats. The tool operates over networks that supply both individual buildings and districts. Although ERIN is valuable by itself for assessment of arbitrary energy networks for their energy resilience, it is meant to be used in conjunction with other tools and processes. The Guide briefly discusses application of ERIN in conjunction with a web-based application called the Simple Master Planner (SMPL) Tool, created by the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) for energy managers, master planners, and policy makers. SMPL tool provides a graphical interface that allows users to evaluate energy, water, waste, and storm water scenarios for military installations, districts, and campuses.

Finally, as a spin-off the main deliverables, the Annex 73 has developed two additional Guides for Resilient Thermal Energy Systems Design in Cold and Arctic Climates and Hot and Humid climate, which address specifics of design in these conditions, including requirements to the building envelope, heating, ventilating, and air-conditioning (HVAC) and energy supply systems.

Two training events (one face-to-face and one virtual) hosted by the U.S. National Academies of Sciences have been organized to promote results of the Annex 73. Twenty-four technical peer-reviewed paper have been published and presented at the international forums. The Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates has been published by ASHRAE and the Energy Master Planning toward Net-Zero Energy Resilient Public Communities Guide has been submitted to Springer for publication in 2022.

Project duration

2018-2022 (completed)

Operating Agents

Dr. Alexander Zhivov
U.S. Army Engineer Research and Development Center
Champaign, Illinois, USA
+1 217 373 4519
Alexander.M.Zhivov@usace.army.mil

Mr. Rüdiger Lohse
KEA
Karlsruhe, Germany
+49 173 6614070
ruediger.lohse@kea-bw.de

Participating countries

Australia, Austria, Canada, Denmark, Finland, Germany, Norway, United Kingdom and the United States of America

Further information

www.iea-ebc.org

Project Outcomes

1. Background

The Energy Master Planning can be applied to different scales of communities: a group of buildings, a campus, a city, a region, or on the national scale.

Over the past years, several countries, cities and campuses have gained experience in energy master planning [2, 3, 4, 5] that resulted in development, implementation and testing robust solutions allowing meeting their energy objectives. Many of these solutions are described in the book of case studies [6] and became an inspiration for development of the planning methodologies in this project.

One of the examples is the Integrated Energy System in Denmark, which has resulted implementation of energy efficient, environmentally friendly, cost-effective solutions and a significant reduction of the national dependency on oil. As a result of this strategy, the potential for use of the waste heat from thermal power generation is fully utilized, the share of wind energy is currently close to 50 % and the reliability of the power system is among the best in the world.

Another example is a typical U.S. university campus, which has hot water district heating and cooling systems with thermal energy storages and combined heat and power generation, which interacts with the larger power grid.

Finally, in addition to establishing challenging energy-related goals, some government agencies and nations have established mandates/national energy legislation that require development of EMPs.

The Danish Heat Supply Act [7] issued in 1979 has formed the legal framework for the Energy Master Planning and its implementation.

In 2016 the Office of the Assistant Secretary of Defense [8] issued a Memorandum requested that Installation Energy Plan shall be a part of the Installation Master Plan and within three years 75% of U.S. Department of Defense (DoD) installations shall complete such plans.

The EU directives for Energy Efficiency and Renewable Energy [9, 10] request member states in the EU to implement Energy Master Planning at national and municipal level for planning district heating and cooling in cost-effective way. In accordance with these directives the EU directive for Buildings (EBPD) requests member states to implement building regulation, with focus on cost effectiveness, good thermal comfort and full decarbonization until 2050 the latest taking into account that efficient and renewable heat and cold can be transferred to the buildings via district heating and cooling.

2. Goal and objectives

The Annex 73 goal was to develop guidelines and tools that support the planning of Low Energy Resilient Public Communities and that are easy to understand and execute with the following objectives:

- Collect, analyze, and document information about best practice community-wide energy master planning processes and find out how they can be improved
- Develop energy, cost and resilience targets and constraints: definitions, metrics, monetary values
- Develop a database of power and thermal energy generation, distribution and storage technologies and system architectures
- Develop guidance for energy master planning for Low Energy Resilient Public Communities
- Collect and describe business and financial aspects and legal requirements and constraints that can be used for implementation of EMPs for public communities in participating countries
- Integrate the targets, constraints, enhanced system architectures the technology database, and resilience analysis into an interactive modeling and optimization tool
- Provide dissemination and training in participating countries for end users, mainly decision makers, community planners and energy managers and other market partners.

3. Approach

3.1. Case studies

The Annex 73 team studied and documented 32 examples of energy master plans from Australia, Austria, Canada, Denmark, Finland, Germany, Norway and the USA. In each of the participating countries, cases of community master planning have been chosen, studied, and analyzed. These cases included military installations, university campuses, research institutes, hospitals, small communities, towns, and large cities. In most of the analyzed campus cases, the buildings and systems under investigation were publicly owned. Systems include those serving critical infrastructure like data servers or life-sustaining systems. Therefore, resilience and reliability play an important role in the master planning process. Local climate conditions are crucial for the choice of energy supply systems. The described case studies are from different areas of the world, ranging from tropical regions in Australia to icy Greenland. The lessons learned were compiled and compared in the “Annex 73 Case Studies Book.”

3.2. Energy framing goals and constraints.

The Annex 73 also investigated and analyzed framing goals and constraints for building and community energy projects that must be considered when energy master planning is conducted. They cover energy use, emissions, sustainability, resilience, regulations and directives, regional and local limitations such as available energy types, local conditions, costs of energy supply to the community and stakeholders and individual project requirements. An example of such goal is achieving resilient, low energy use communities and low-cost energy supply for the community and stakeholders.

For holistic energy planning, it is essential to clearly define energy-related requirements and long- and short-term energy goals, important constraints, and community priorities, at the beginning of a study. Energy use requirements are typically established by a country, state, local authority, project team, building owner, or other stakeholder. Constraint limits should be evaluated as either hard “must achieves” for the project design or soft “good to have”. Targets (or goals) are often desires (what one would like to achieve) and may or may not lead to requirements.

Energy goals that can be used in the comparison of alternatives may include:

- Energy use (site and primary)
- Total cost of energy supply to individual buildings and on the community level
- A minimum requirement to energy system resilience
- Use of energy from renewable energy sources
- Environmental impact, including maximum allowable emissions from use of fossil fuels
- System economics.

While energy use related constraints can profoundly impact building technology selection, other constraints, e.g., related to energy system resilience, can be fulfilled by installing technologies in secure places and creating strong building structures (hardened against flooding and building stronger/better insulated walls and roofs).

Energy framework constraints can be used for energy system architectures and technology database down selection:

Connection (or no connection, e.g., in remote or island locations) to outside community (which determines categories of system architectures);

- Existing or potential energy supply from outside the community boundaries: power, hot water, steam, chilled water
- Fuel available: Gas, coal, fuel oil, biomass, biogas, propane
- Available renewable energy sources: solar thermal, solar photo voltaic (PV), wind energy, geothermal, sea/river water cooling
- Current energy systems on the campus: centralized or decentralized (no distribution lines available)
- Describing existing energy system or selection of future energy systems to be considered (centralized or decentralized)
- Operational and personnel constraints (consideration that some operators may not have skills to operate certain types of systems)
- Environmental constraints for using different types of technologies: e.g., water, emissions from a central heating plant (CHP), etc.
- Building space constraints (no mechanical room for decentralized systems, thermal storage, etc.)
- Community space constraints (e.g., for seasonal storage, PV, or thermal solar panels array)
- Community layout constraints (e.g., for placing central heating or cooling systems’ pipes).

lists examples of natural and imposed (manmade) constraints that impact selection of system architecture and technologies.

Long-term energy goals could include the reduction by a desired percentage of site or source energy use by a target year compared with a Baseline, or the achievement of a Net-Zero site/source energy community within a given timeframe. These goals lead to decision metrics that will be used to decide between alternative solutions. They help to focus the study and define “success.” It is possible that the goals turn out to be infeasible/unreachable, in which case the goals can be adjusted once quantitative data are available. The most common energy requirements, goals, and constraints may be categorized as

- Community, building cluster and facility level
- Operational constraints
- Constraints based on natural threats
- Locational resources available: district chilled and hot water, steam, water, electricity grid, natural gas pipeline, liquid fuel
- Energy supply constraints: power supply limitations, gas supply limitations, availability of energy from renewable sources
- Requirements to energy systems resilience.

Table 1. Constraints that narrow energy system architecture and technologies options.

Natural Constraints		Imposed Constraints				
Category	Constraint	Category		Constraint	Category	Constraint
1. Locational Threats	Regional or local air quality	3. Energy and Water Distribution and Storage Systems		Natural Gas	5. Indoor Environment	Air temperature
	Low lying area (flooding)			Electricity		Air Humidity
	Extreme temperatures			Fuel Oil		Illumination level
	Extreme humidity			Chilled water		Indoor air quality
	High winds			Hot water		Radon
	Fire			Steam	6. Existing equipment in buildings and district systems	Space heating
	Lighting			Water		Space cooling
	Ground threats (volcano, mud slide, earthquake)	4. Building related	Energy	Energy use (site)		Ventilation
2. Local resources available	Solar			Energy use (primary)		Humidity control
	Wind			Energy Efficiency		Water heating
	Biomass		Environmental	Renewable energy		Food preparation
	Land or roof area available for renewable energy technologies			Emissions		Waste handling
	Natural gas		Operational	Resilience		Electricity generation
	Electricity from the grid			Financial/costs		District steam
	Liquid fuels			Maintenance (e.g., simplicity, low cost)		District hot water
	Hot water			Workforce limitations		District chilled water
	Chilled water			Other building owner limitations		

3.3. Energy system resilience

Energy resilience is defined as the ability to prepare for and recover from energy disruptions that impact mission assurance [11]. Resilience of the energy system impacts the primary function of military installations, hospitals, and education campuses during disruptions. Throughout the history of energy systems, major disruptions of energy supply (both electrical and thermal) have degraded critical capabilities and caused significant social and economic impacts to private and public communities. Therefore, resilience must be an integral goal of the community-wide energy master planning process, and application of energy resilience principles are important during design of new and upgrade of existing energy systems. Best practices for resilient electric and thermal energy systems favor the use of installed energy sources rather than the use of emergency generation for short durations and promote the use of multiple and diverse sources of energy and favor energy resources originating within the community

Electric and thermal energy delivery may be visualized as having three delivery mechanisms or layers (Figure 1). The first delivery mechanism resides internal to the facility; it is the building-level power infrastructure for electric energy systems and building envelope and its mechanical systems for thermal energy supply. The second delivery mechanism is the emergency, or backup, energy systems directed to the facility from outside of the building but sourced from on-site power and thermal energy generation. The third delivery mechanism is the full load delivered to the facility under normal operating conditions; this is commonly comprised of prime power or power delivery from an electric utility for electric systems; and steam, hot water, and/or chilled water delivered from the campus, building cluster, or some location outside the campus plant.

A variety of energy system options can be used to supply power, heating, and cooling to campuses; these options vary by the architectures and technologies used, and by whether they apply to individual buildings, building clusters, campuses, or even entire communities. Design and evaluation of system resilience measures should be based on requirements established by mission operators.

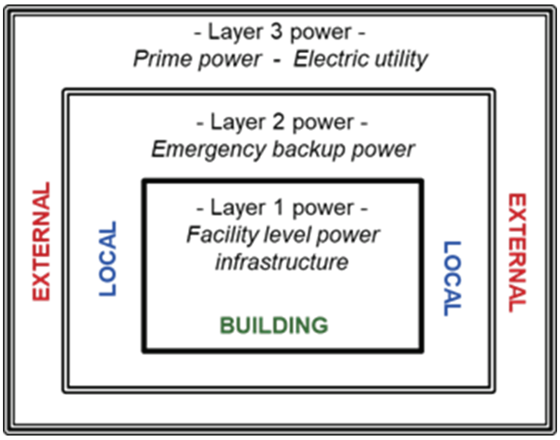


Figure 1. Layers of power supply to mission-critical facilities.

A quantitative approach to resilience of system supplying energy to the building proposed by the project team can include (but is not limited to) the following metrics:

- Energy System Robustness (ER)
- Energy System Recovery time or Maximum Time to Repair (MaxTTR)
- Energy Availability (EA)
- Energy Quality (EQ).

The first three parameters are critical for selection of layers two and three energy supply system architecture and technologies it is comprised of to satisfy requirements related to energy system resilience.

Requirements for Energy Availability and Energy System Recovery Time depend on:

- Criticality of the mission being served by the system,
- System repairability, which has significant dependence on remoteness of the facility hosting the mission, and
- Redundancy of facilities that can serve the same critical function and the layer one energy system capacity.

Energy Quality (EQ) is another important quantitative metric for the energy system that serves critical functions; EQ should be considered as a design parameter for internal building (layer one) energy systems. Most of the mission-specific EQ requirements, including limitation on short-term power interruptions, voltage and frequency variations, harmonics, etc. can be handled by the building-level energy systems.

Building-level electric systems (nanogrids) generally include redundant or backup components and infrastructure for power supply, uninterruptible power supply, automatic transfer switches, data communications connections, and environmental controls (e.g., air-conditioning, fire suppression). Nanogrids also include various security devices that can be designed to provide power with a severe demand on the stability and level of the frequency, voltage, and waveform characteristics of the uninterruptable electrical power to mission-critical equipment, and that can operate in an islanded mode between 15 minutes and several hours. It is important to account for the latter capability when requirements for maximum energy supply downtime are established.

Using the Energy Robustness metric, we can quantify the overall resilience of a system in two phases: absorption of the event, and recovery (Figure 2).

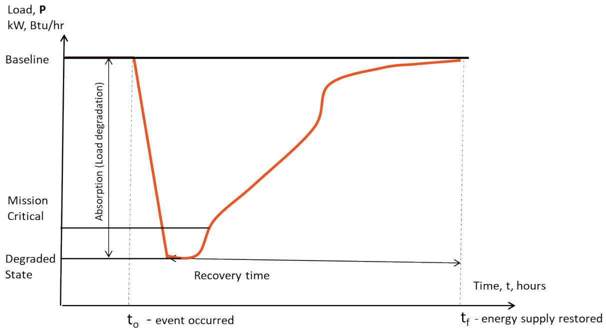


Figure 2. System response to a disruptive event.

Immediately after the event there is a sharp drop in the load available to mission. For electric energy systems, duration of phase one is much shorter than for thermal energy systems, unless thermal systems are used for processes using steam or hot water. When mission-critical buildings have an energy efficient building envelope with a high thermal storage capacity ~~mass~~, it can take hours or days before the internal air temperature reaches habitability or sustainability thresholds. This change from the Baseline to the degraded state represents the robustness of the system to that particular event. The time required to restore the system to its baseline state is referred to as recovery. The smaller the change in load available to mission and the shorter the recovery time, the more robust the system.

Energy Robustness, ER, of the system to any particular event can be quantified using Equation 1 and is illustrated by the area between the line showing the baseline mission availability and the curve representing the actual mission performance over time. The smaller the area between the Baseline and the curve, the more resilient the system. Robustness will be measured on the scale between 0 and 1, where 1 is the most resilient system:

$$ER_{m.c.} = \frac{E_{event}}{E_{m.c.}} \qquad (1a)$$

$$ER_{baseline} = \frac{E_{event}}{E_{baseline}} \qquad (1b)$$

where $ER_{m.c.}$ and $ER_{baseline}$ are system robustness measured against the mission-critical load and the baseline load; $E_{m.c.}$, and E_{event} are energy supplied to the building during the period of time between t_o and t_f with the baseline load, mission-critical load and load degraded due to event, respectively:

$$E = \int_{t_o}^{t_f} P(t)dt \qquad (2)$$

Depending on mission needs, it may be more important to prioritize either absorption or recovery.

Energy Availability is a measure of the readiness of a system or component to perform its required function and is usually expressed as a function of equipment downtime as shown in Equation 3.

$$EA = \frac{Uptime}{Uptime+Downtime} \qquad (3)$$

This metric is used to evaluate the performance of the energy in terms of percentage of time it is available for the mission. For example, if an event occurs that reduces energy availability to 0.99, then the average expected weekly downtime of the mission is about 100 minutes. If a more resistant system is only reduced energy availability to 0.999, the expected weekly downtime for the mission is approximately 10 minutes.

The Guide offers a methodology that will help mission operators to determine requirements to Energy Availability and Recovery based on three factors: mission criticality, facility remoteness/repairability and redundancy (Table 2).

The Resilience Requirement listed in Table 3 stratify each Resilience Metric listed in Table 2. Each Resilience Metric is split into two levels of facilities: Primary and Secondary, which in turn have two levels of requirements (i.e., low/moderate, moderate/significant, significant/high) to energy system resilience ranging from Low (0) to High (4). Such stratification of each Resilience Metric creates more accurate scenarios fitting to the facility and mission requirements.

Table 2. Determination of resilience requirements.

Resilience Metric Requirement	Resilience Phase	
	Availability	**Recovery**
Low	Criticality: **Low-Moderate** Remoteness: **Low** Facility Redundancy: **Yes**	Criticality: **Low** Remoteness: **Low-Moderate** Facility Redundancy: **Yes**
Moderate	Criticality: **Low-Moderate** Remoteness: **Moderate-Significant** Facility Redundancy: **Yes**	Criticality: **Low-Moderate** Remoteness: **Moderate** Facility Redundancy: **Yes**
Significant	Criticality: **Moderate-High** Remoteness: **Significant-High** Facility Redundancy: **No**	Criticality: **Moderate-Significant** Remoteness: **Significant-High** Facility Redundancy: **No**
High	Criticality: **Significant-High** Remoteness: **High** Facility Redundancy: **No**	Criticality: **High** Remoteness: **Significant-High** Facility Redundancy: **No**

The availability of multiple categories will facilitate the ability of design teams to identify the most correct resiliency requirement for the project at hand. The tables represent two category states for each of the four Resilience Metric. Expansions of tiers for Resilience Metric Requirements creates three properties of a process:

- An additional level of granularity for more accurate direction leads to the most appropriate category of resilience and assist in the ability to select the most appropriate category.
- More flexibility for a project to identify the lowest Resilience Metric Requirement level that is appropriate.
- Avoid unnecessary complexity that increases cost.
- Assistance to a project team to resist invention of a resilience level that is not represented in less granular criteria.

For thermal energy systems, the Maximum Single Event Downtime can be defined in terms of how long the process can be maintained or the building remains habitable (habitability threshold) or the thermal environment shall be maintained above the sustainability threshold level to protect the building against damage from freezing of water pipes, sewer, fire suppression system, protect sensitive content, or the start of mold growth during extended loss of energy supply with extreme weather events. Results of Temperature Decay Tests along with parametric studies of indoor air temperature decay using EnergyPlus-based building energy modeling presented in the Guide, showed that high building mass contributes significantly to the thermal resilience of the building, along with the higher building air tightness and a higher thermal insulation (Table 3). If there are critical processes requiring uninterruptable source of thermal energy (like sterilization), these must be considered separately. Evaluating Energy System Robustness. Existing or proposed power or thermal energy system is evaluated for meeting required resilience using deterministic method illustrated in Figure 3. Based on results of all threat/all hazard assessment conducted for the area of interest with identified critical assets, the most common natural disasters, accidents, and manmade threats are identified, ranked and rated and the most critical, called Design-Basis Threats (DBTs) are selected to be addressed in the resiliency analysis integrated into the EMP.

For selected DBTs, the higher-intensity events have a greater risk of causing energy system component failure, but they occur less frequently. Figure 4 provides an example of a fragility curve for a particular component that shows the probability of component failure according to the intensity of an event.

Energy robustness of existing or proposed power or thermal energy system is evaluated for meeting required resilience using deterministic method illustrated in Figure 3.

Based on results of all threat/all hazard assessment conducted for the area of interest with identified critical assets, the most common natural disasters, accidents, and manmade threats are identified, ranked and rated and the most critical, called Design-Basis Threats (DBTs) are selected to be addressed in the resiliency analysis integrated into the EMP.

Table 3. Recommended resilience requirements to power systems serving mission-critical facilities.

Resilience Metric	Facility Level	Resilience Sub-Metric	Category	Degraded State Availability	Acceptable Average Weekly Downtime (Minutes)	Maximum Single Event Downtime (Minutes)
Low	Primary	Low	LP/1	0.92	806.4	2,419
		Moderate	LP/1+	0.95	504	1,500
	Secondary	Low	LS/0	0.9	1008	3,024
		Moderate	LS/0+	0.92	806.4	2,419
Moderate	Primary	Low	MP/2	0.99	100.8	302
		Moderate	MP/2+	0.995	50.4	150
	Secondary	Low	MS/1	0.95	504	1,500
		Moderate	MS/1+	0.99	100.8	302
Significant	Primary	Moderate	SP/3	0.999	10.08	30
		Significant	SP/3+	0.9995	5.04	15
	Secondary	Moderate	MS/2	0.95	504	1,500
		Significant	MS/2+	0.99	100.8	302
High	Primary	Significant	HP/4	0.9999	1.008	3
		High	HP/4+	0.99999	0.1008	0.3
	Secondary	Significant	HS/3	0.9995	5.04	15
		High	HS/3+	0.9999	1.008	3

P = Primary Facility / Mission
S = Secondary Facility / Mission
L = Low Resilience Metric
M = Moderate Resilience Metric
S = Significant Resilience Metric
H = High Resilience Metric
+ = Highest 10% of a Specific Resilience Metric Range
0 = Resilience Metric Range – Lowest Resilience Metric Range
1 = Resilience Metric Range – Scaled 0 to 4, with 4 the highest level of resilience metric
2 = Resilience Metric Range – Scaled 0 to 4, with 4 the highest level of resilience metric
3 = Resilience Metric Range – Scaled 0 to 4, with 4 the highest level of resilience metric
4 = Resilience Metric Range – Highest Resilience Metric Range

Table 4. Single event downtime for buildings with different mass, airtightness and energy efficiency of the building's envelope.

Building Parameters	Temp ODB	Mass Building			Frame Building		
		Typical/Post 1980	Low Efficiency	High Efficiency	Typical/Post 1980	Low Efficiency	High Efficiency
Walls R-value, °F·ft^2·hr/Btu ([m2·K]/W)		20.5 (3.6)	40 (7.0)	50 (8.8)	20.5 (3.6)	40 (7.0)	50 (8.8)
Roof R-value, °F·ft^2·hr/Btu, ([m2·K]/W)		31.5 (5.5)	45 (7.9)	60 (10.6)	31.5 (5.5)	45 (7.9)	60 (10.6)
Air Leakage, cfm/ft2 at 0.3 in. w.g. (L/s.m2 @75Pa)		0.4 (2)	0.25 (1.25)	0.15 (0.75)	0.4 (2)	0.25 (1.25)	0.15 (0.75)
Window (R-value, °F ft^2·hr/Btu, U value, W/(m2·K)		Double Pane; R = 1.78 / U = 0.56	Double Pane; R= 3.34 / U=0.3	Triple Pane; R= 5.25 / U=.19	Double Pane; R = 1.78 / U = 0.56	Double Pane; R= 3.34 / U=0.3	Triple Pane; R= 5.25 / U=0.19
MaxSEDT Hab. (60°F/15.6°C)	-60 °F -51.1 °C	< 1 hours	2 hours	5 hours	<< 1 hour	1 hours	2 hours
MaxSEDT Sust. (40°F/4.4°C)		9 hours	28 hours	41 hours	4 hours	14 hours	21 hours
MaxSEDT Hab. (60°F/15.6°C)	-40 °F -40 °C	1 hours	3 hours	10 hours	< 1 hour	2 hours	4 hours
MaxSEDT Sust. (40°F/4.4°C)		20 hours	36 hours	51 hours	10 hours	18 hours	24 hours
MaxSEDT Hab. (60°F/15.6°C)	-20 °F -28.9°C	2 hours	6 hours	15 hours	1 hour	3 hours	6 hours
MaxSEDT Sust. (40°F/4.4°C)		31 hours	46 hours	60 hours	15 hours	22 hours	28 hours
MaxSEDT Hab. (60°F/15.6°C)	0 °F -17.8°C	3 hours	13 hours	29 hours	2 hours	5 hours	9 hours

Building Parameters	Temp ODB	Mass Building			Frame Building		
		Typical/Post 1980	Low Efficiency	High Efficiency	Typical/Post 1980	Low Efficiency	High Efficiency
MaxSEDT Sust. (40°F/4.4°C)		43 hours	59 hours	90 hours	21 hours	28 hours	33 hours
MaxSEDT Hab. (60°F/15.6°C)	20 °F -6.7°C	10 hours	28 hours	45 hours	3 hours	8 hours	15 hours
MaxSEDT Sust. (40°F/4.4°C)		60 hours	78 hours	95 hours	28 hours	35 hours	40 hours
MaxSEDT Hab. (60°F/15.6°C)	40 °F 4.4°C	29 hours	54 hours	72 hours	8 hours	17 hours	23 hours
MaxSEDT Sust. (40°F/4.4°C)		93 hours	112 hours	123 hours	41 hours	47 hours	50 hours

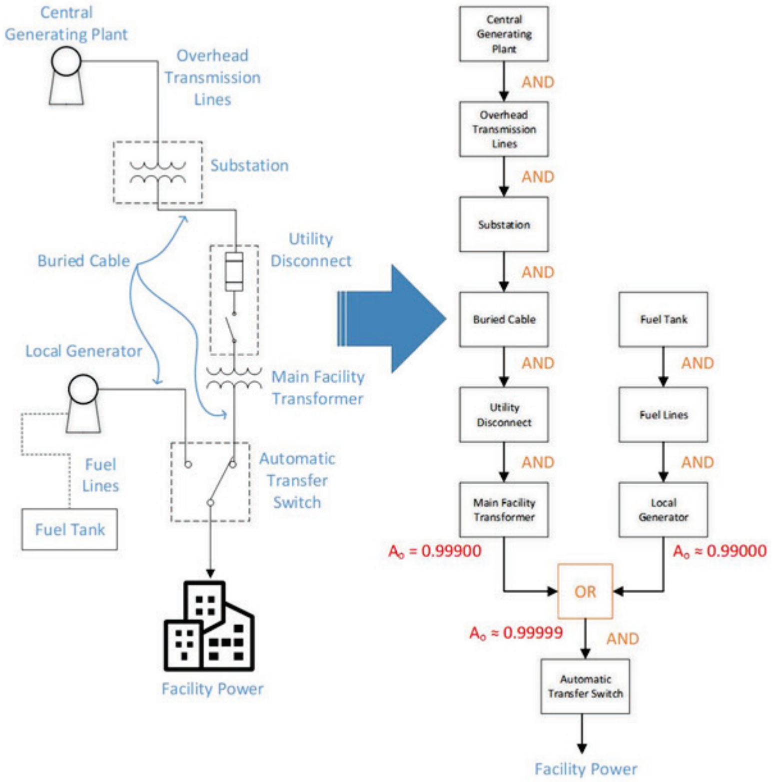


Figure 3. Reliability block diagram for a typical power system.

For selected DBTs, the higher-intensity events have a greater chance of causing energy system component failure, but they occur less frequently. Figure 4 provides an example of a fragility curve for a particular component that shows the probability of component failure according to the intensity of an event.

All components in a system are uniquely vulnerable to a set of events. For example, exterior generators may be vulnerable to flooding, whereas supervisory control and data acquisition (SCADA) controlled switchgear may be more vulnerable to cyberattacks.

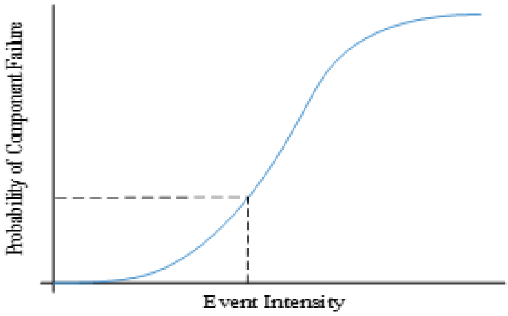


Figure 4. Example fragility curve for the notional event.

If fragility curves for individual components are available, then the probability of component failure associated with an event can be incorporated into the system availability model. However, in many cases it may be more practical to consider certain key components as having failed due to the event. For the deterministic approach, this clearly identifies single points of failure or areas that require additional hardening measures (e.g., burring cables, raising steam lines and equipment, creating meshed networks for hot- and cold-water pipes, erecting flood walls). These system alterations need to be designed, installed, and commissioned, and performance of these systems must be tested on a regular basis. Especially in preparation for events. these would improve the absorption and reduce the recovery time. A contingency event can affect energy availability to the mission. For example, in the power system shown in Figure 4, a wind event disables only overhead transmission lines. Since backup power can be immediately supplied by emergency generators, mission loads can continue to operate. However, until the transmission lines are restored, the likelihood of failure is significantly increased. Figure 5 shows an example of mechanical cooling system schematic. As a performance metric, mechanical system availability considers interdependencies between physically isolated fluid systems (i.e. chilled water, condensing water).

3.4. Energy Planning as a Part of the Community Master Plan

For existing large areas, the planning process is complex, and includes consideration of future use and energy costs as well as of maintenance and operation of existing infrastructure. Implementation plans for energy systems cover many years of actions to increase efficiency, resilience, and reliability. These plans are important to provide the scope, schedule, and security to projects funded either directly or using a third-party financing.

The process of building efficient, sustainable, resilient communities requires careful coordination between stakeholders, including master planners, energy planners, and building designers. These stakeholders work at differing levels of detail and use different planning horizons, which may lead to suboptimal decisions for the community as a whole. Coordinating the myriad stakeholders involved in community planning can be a challenge.

Three levels of stakeholders can readily be identified. At the highest level of abstraction, master planners think in terms of long-term sustainability goals, including national energy strategy, community layout, transportation, and street design; in this stage, planners work to break down barriers between sectors and cities. To address sustainability, master planners have to look at the society as a whole and extend the length of their view to 25 years or more (Case et al. 2015). Energy managers fall within the middle tier of abstraction; the focus of their work is on the local community or campus projects, which may vary between longer-term energy infrastructure projects, such as district energy systems, to medium- or near-term projects, such as building retrofits designed to meet community energy goals. Finally, the building (or infrastructure) designer's efforts occupy the most detailed level of abstraction. These engineers must create designs for a specific project that can be shown to be effective, buildable, biddable, and cost effective.

Integration of energy planning into community planning requires a holistic approach to the planning process and relies on new concepts, instruments and tools to be available to master planners, energy managers, decision makers and stakeholders. Energy master planning is a complex process that includes cultural, organizational, technical, legal and financial aspects. The process is facilitated by a common terminology, a clear roadmap, and well-defined goals.

3.5. Energy Master Planning Concept

The objective of the community/installation Energy Plan is to produce a holistic roadmap that enables planners to work constructively towards various framing energy goals within defined community specific constraints. The Energy Master Planning concept described in this Guide differs from previously developed concepts [2, 3, 8] in such a way, that in addition to meeting community's framing energy goals, it integrates development of a highly resilient "backbone" of energy systems that allow communities to maintain critical missions and service operations effectively during extended outages over a range of emergency scenarios, whether caused by weather, manmade events or aging infrastructure (Figure 6).

The integrated approach described in the Guide results in cost-effective operation of energy systems under normal (blue sky) conditions and in a less vulnerable, more secure and more resilient energy supply to the community's critical mission functions during emergency (black sky) scenarios. It provides a framework for the planning process and outlines the main steps, which include: (1) establishment of energy framing goals and constraints, (2) assessment of community's critical missions and functions, (3) assessment of community specific threats, (4) establishment of energy requirements for normal and mission-critical functions (5) assessment of the current situation (baseline) to understand existing gaps against framing goals and constraints, and (6) development of future alternatives, including "business as usual" (Base Case) and more advanced alternatives of energy systems. Quantitative metrics should be used to compare baseline, base case, and future alternatives.

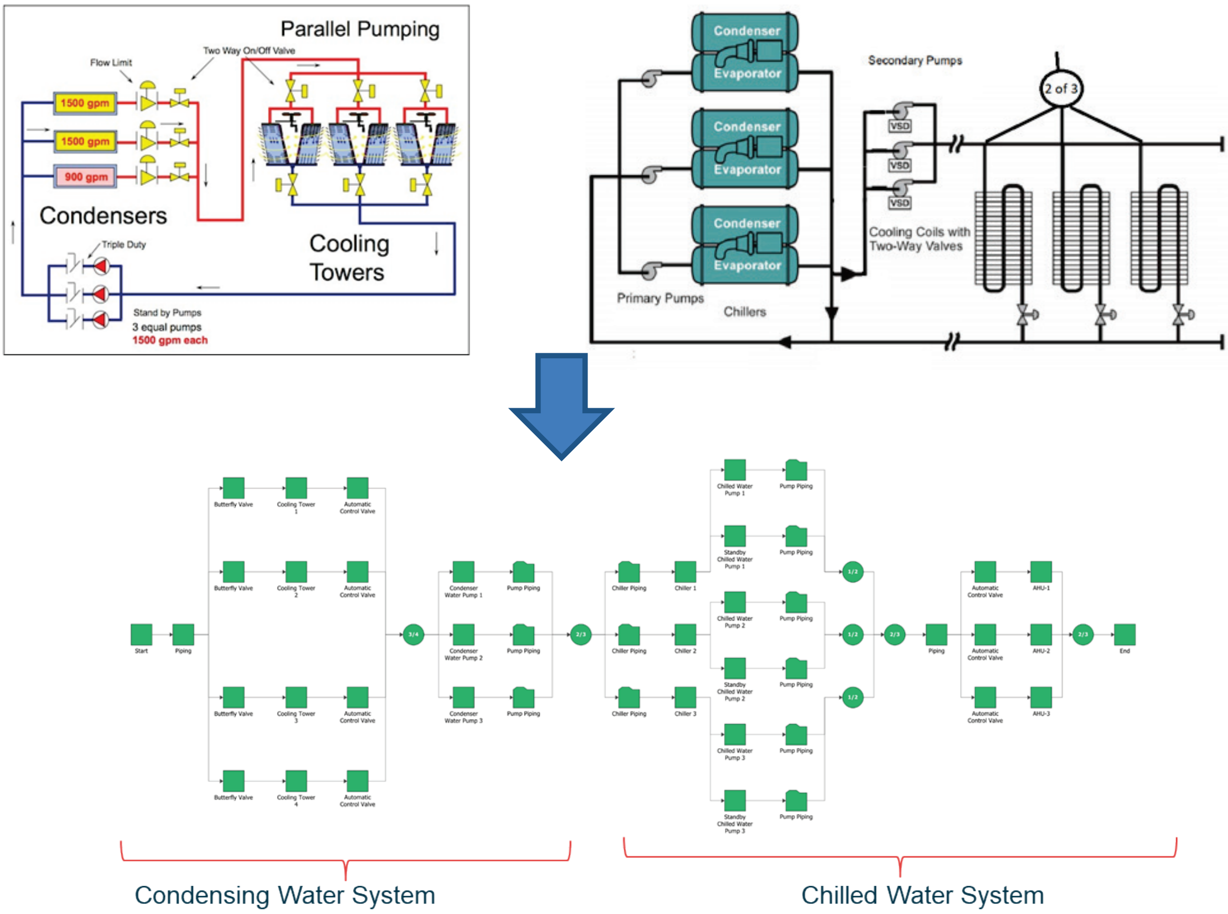


Figure 5. Availability methodology for mechanical cooling system resilience analysis.

“Blue sky” and “black sky” alternative architectures can be built upon the database of technologies and architectures summarized from internationally available best practices. Alternatives established under normal conditions (blue sky) consider energy goals, constraints, loads, and the operation of all buildings and systems. However, selection of architecture of different alternatives for energy systems during this phase of the planning process may already consider the implication of their characteristics and their function on the resilience of systems serving mission-critical facilities under emergency conditions.

The planning process for mission-critical buildings and functions addresses only critical loads under emergency (black sky) conditions. This part of the process includes steps that allow planners to narrow down the scope of buildings and operations and their loads to those that are mission-critical, that assess threats specific to locality and function of the installation and their impact on energy systems’ degradation, and that calculate energy requirements for mission-critical functions. Planners will evaluate gaps in existing systems resilience; and develop future alternatives of systems that provide the required level of energy assurance to mission-critical functions, including “business as usual” (Base Case) and more advanced alternatives of energy systems with consideration of, but not limited to, those developed under the “blue sky” scenario. At this point of analysis, there is an opportunity for iteration between alternatives developed under these two scenarios. Final steps of the integrated Energy Master Planning process include comparison of different alternatives against the framing goals established earlier using quantitative and qualitative metrics.

At this point, iteration may be required to modify or create new alternatives if the goals were not met. Once decision makers have selected a preferred alternative, they must prepare an implementation plan that includes an investment strategy and projects required to achieve the plan. Based on the situation at specific campuses, the breadth and depth of improvements under different alternatives may differ to reflect existing plans and timing for new construction, major and minor renovation of the building stock and utilities, criticality of their missions, and availability of resources. Also, the quality of the data available for development of the Baseline and the Base Case and energy requirements for mission-critical operations at specific installations may vary. This may result in differences in the realization of the described concept at specific campuses.

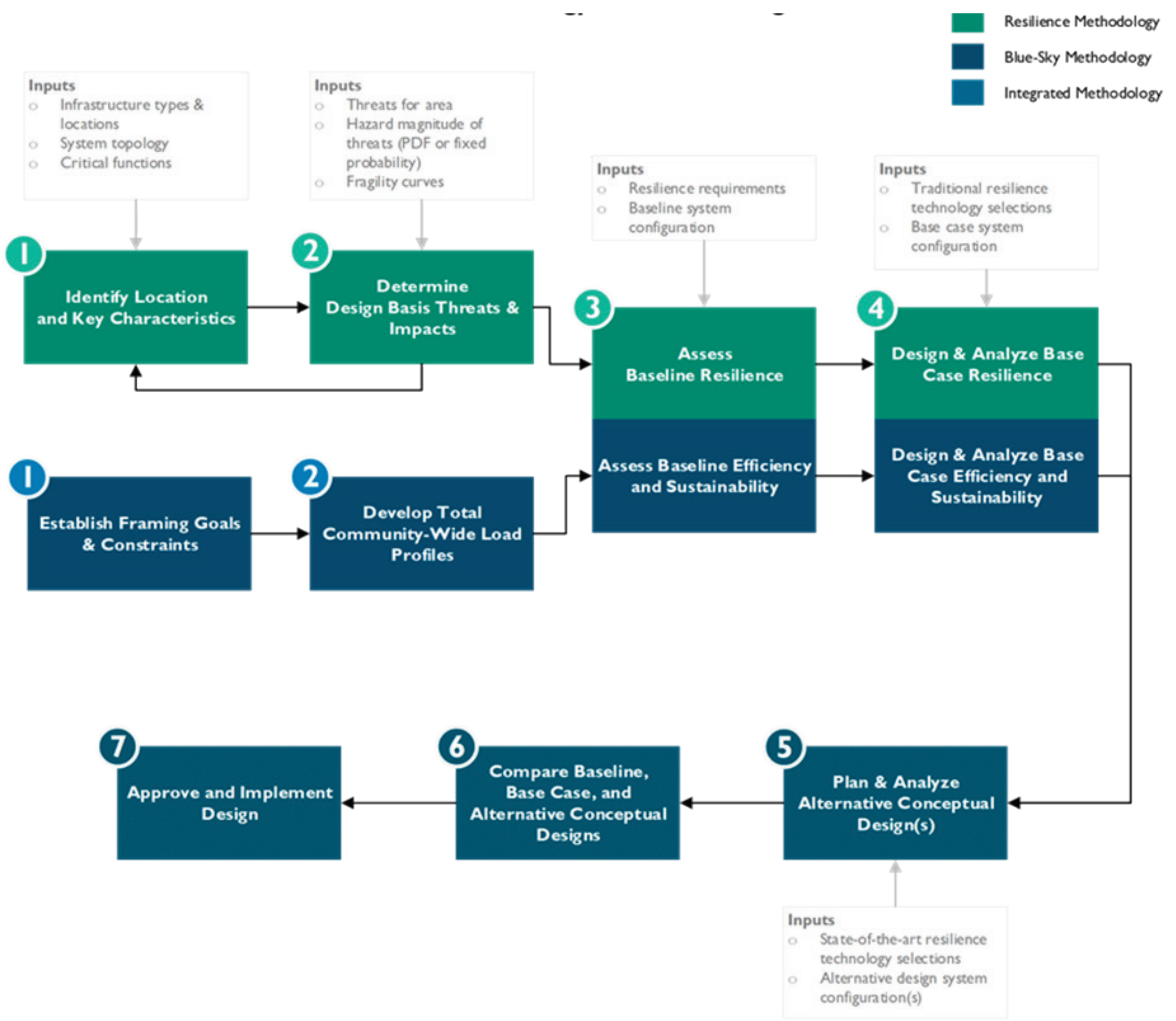


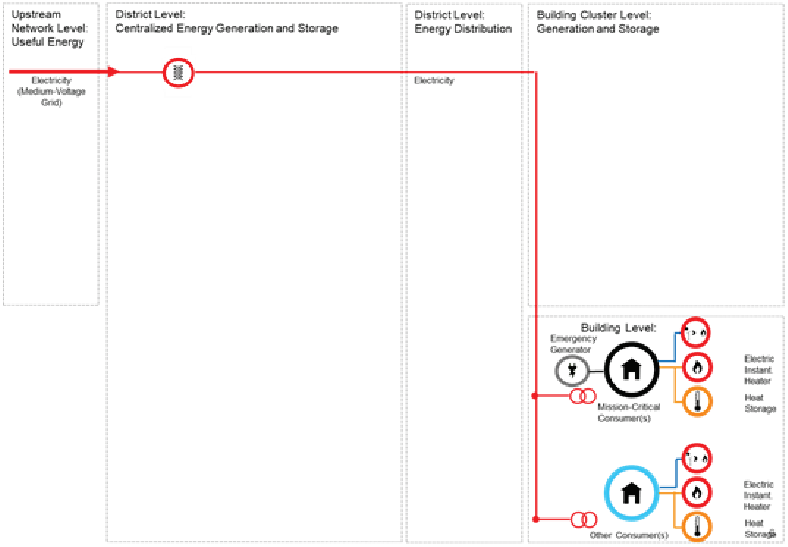
Figure 6. Integration of Energy Systems Resilience Analysis into the Energy Master Plan (EMP).

3.6. Selection of energy system architecture

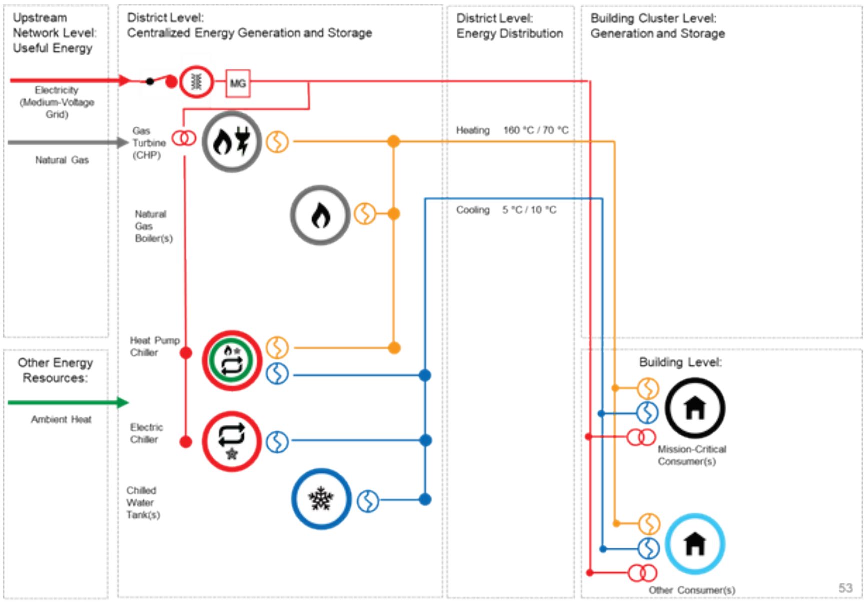
A list of power and thermal energy system architectures technologies and technologies they employ was generated by the Annex 73 team from case studies, best practices collected using surveys conducted in the USA and in Europe from district energy associations, discussions at the ASHRAE Technical Committee (TC) 7.6 “Public Buildings” working group meetings in 2018 and 2019, and from previous experience and research conducted by the Annex 73 team members. These system architectures and technologies have been categorized and documented with their characteristics (cost and performance), application, pros and cons described. Obtained information can be used for further detailed analysis of the EMP baseline and of different alternatives including the Base Case and more advanced concepts to be considered in new development (“greenfield”) and/or renovation/extension (“brownfield”) projects. Different system options can be considered on the building level, building cluster level or a community level. Selection of these alternatives should consider the existing status of these systems, the goals and objectives of the project, including improvement in systems resilience, local constraints, and economic and non-economic co-benefits.

The architecture and technologies used in a specific system may include components from several system generations to accommodate the end user needs, whether those components include new development (greenfield) projects, expansion of an existing system or modernization and renewal of an aging system. For example, some critical hospital buildings and pharmaceutical facilities may need to provide steam to accommodate certain end users, while most other end users may be sufficiently served by hot water service.

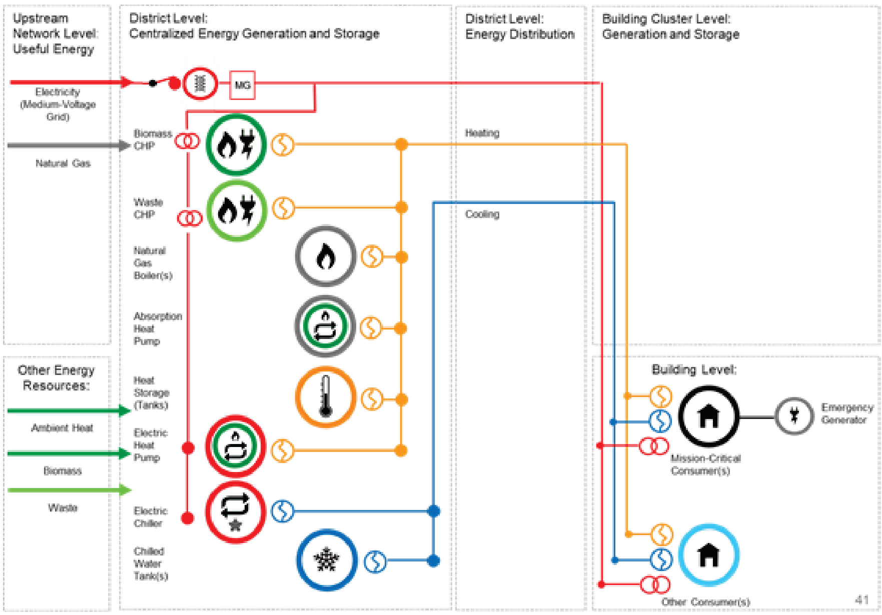
The Guide offers a library of more than 50 examples for energy system architectures, which cover centralized and decentralized, fossil-fuel-based, and renewable systems (see Figure 7 for examples). The library includes general solutions as well as solutions for special situations like remote locations/islands or solutions with electrical enhancements and microgrids to allow islanding power systems from the main electric network.



a. Generic power-only system with buildings heating and cooling using electric boilers and chillers

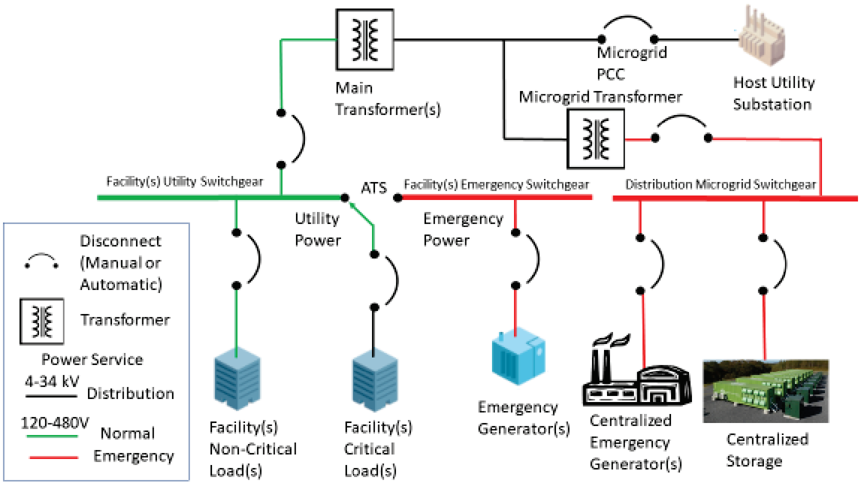


b. District heating, cooling and power systems (Case Study from UT Austin Medical Center)



c. Generic power, heating and cooling systems with CHP base load generation seasonal storage, waste heat use, etc.

Figure 7. Examples of energy systems architectures.



d. Notional microgrid with distribution-level centralized emergency generators and distribution-level centralized storage.

Figure 7. Examples of energy systems (architectures (Cont'd).

The library offers energy system designs for different climate zones or fuels, for densely populated communities and small, remote communities, and for communities with or without critical buildings. To assist the Energy Master Planning process, a library of system architecture templates includes a description of the application, advantages and disadvantages for each template.

3.7. Selection of energy system technologies

Technologies for each system architecture can be selected from a technology database that includes information on technical, economic, and reliability characteristics of different technology archetypes along with a short technology description and application. Selection of technologies can be narrowed down by applying constraints related to availability of different fuels and space available for installation specific technologies and plants.

The technologies database was developed based on the information available from various sources. These included the NZP/System Master Planning (SMPL) tool, MIT LL Energy Resilience Analysis (ERA) tool, REOpt tool (reopt.nrel.gov), U.S. Department of Energy CHP factsheets, Danish Energy Agency Technology Catalogue and information provided by International District Energy Association, EATON, Schneider Electric, TKDA, Ramboll and GEF. The technology reliability data was provided by the U.S. Army Corps of Engineers Power Reliability Enhancement Program (PREP). The database is comprised of multiple energy conversion, distribution, and storage technologies that can be integrated by energy planners into energy system architectures.

The MS Word® version of the database with fixed values of technology characteristics presented in this Guide is complemented by an Excel® version that is integrated into the Energy Master Planning tool. The Excel® database can be updated and adjusted based on specific fuel prices, currency, and national characteristics; it also includes text boxes and attachments for guidance. The MS Word® version is limited to fixed 2020 values regarding economic assumptions and does not include automatic calculations, e.g., the levelized cost of electricity (LCOE) calculation.

The database is structured (Figure 8) to include the following categories:

- Electric systems
- Heat supply systems
- Chilled water systems
- Natural gas systems
- Miscellaneous.

4. Energy Resilience of Interacting Networks (ERIN)

4.1. ERIN tool

The ERIN tool has been developed to support an energy master planning process that allows for the assessment of the resilience of energy supply systems to various DBTs. The tool operates over networks that supply both individual buildings and districts. These networks are comprised of components (loads, generation, distribution/routing, storage, and transmission assets) and connections. These connections form the topology of the network – what is connected to what. Multiple flows of energy can be modeled: notably, both thermal (heating/cooling) and electrical flows and their interactions.

This network of components is subject to various scenarios that represent one or more ideal ("blue sky") cases as well as DBTs ("black sky" events). Each scenario has a probability of occurrence and zero or more intensities associated with it such as wind speed, vibration, water inundation level, etc.

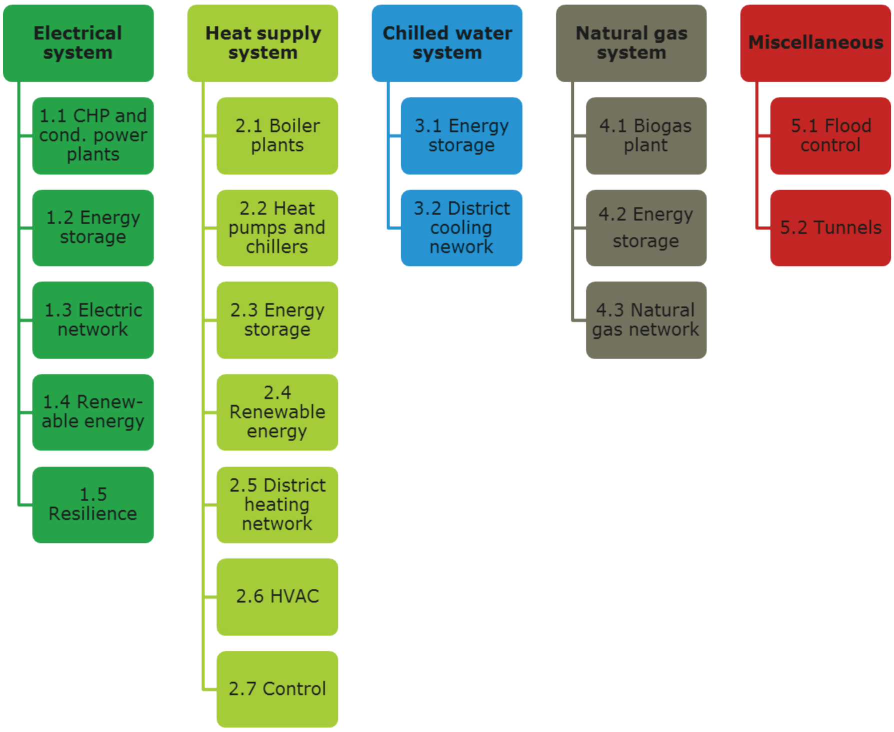


Figure 8. Database structure.

Fragility curves are used to relate the scenario's Design-Basis Threat intensities with the percentage chance that a given component will fail to work under the duress of the scenario.

Examining the performance of the network while considering the possibility of failure due to various threats allows resilience metrics, described in section 3.3., such as Energy Robustness (ER), Energy System Recovery Time (Maximum Single Event Downtime or "MaxSEDT"), or Energy Availability (EA) to be calculated. This can, in turn, help planners to see whether a proposed system or change to an existing system will meet their threat-based resilience goals.

Figure 9 shows the information flow and process for using the calculation tool. The goal of the process is to assist a planner in selecting appropriate architectures, configuring them for their local situation, and assessing them for their costs, energy usage, and resilience benefits for relevant DBTs. This allows users to compare multiple architectures or different configurations of the same architecture (using different types or grades of equipment, for example).

The process begins with the user's description of goals, site constraints, and available resources as shown in Figure 9. These criteria can be used to assist the user in selection (filtering out irrelevant choices and/or recommending especially relevant choices) and evaluation (tracking status of a design versus goals and/or constraints).

Next, the planner can proceed to architecture selection from a database of architectures (see section 3.6). This selection can be guided based on site criteria. For example, if the user specifies that they have electrical and heating loads only (i.e., no cooling load), only those architectures with heating and electrical supply will be made available to browse from. An architecture is a pre-constructed template for how certain types of technologies are typically connected. The architecture, once selected, must also be configured to match the user's unique situation. Configuration involves adjusting the selected architecture to better represent the desired situation by choosing specific equipment, specifying multiples, etc. Potential component technologies that fit with the architecture are looked up in a database of technologies. This results in the creation of an input file to be used by the resilience tool "engine."

Scenarios have an occurrence distribution, a duration, an optional maximum number of occurrences during the simulation, and, optionally, various DBT intensities. DBT intensities specify things like the wind speed during a hurricane, the inundation depth during a flood, and the Richter scale during an earthquake. A scenario can also specify whether normal reliability (failure and repair under typical conditions) should be considered or not. Probability of occurrence can be based on actual data for an event.

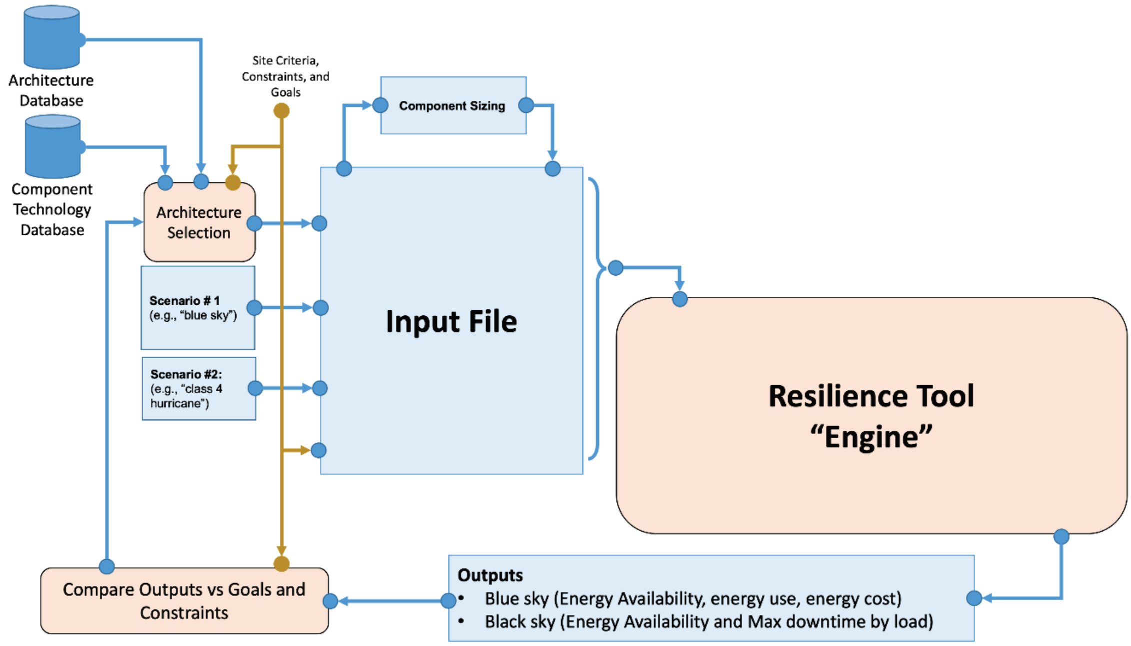


Figure 9. Overall energy and resilience assessment process.

A component technology database stores information about actual components that can be used by the tool. Components represent equipment on the network: chillers, boilers, backup generators, UPS systems, TES tanks, fuel drums, etc. If the user has specific information about a given component, they can specify it. Otherwise, the information can be queried from the component technology database. Once the architecture selection, configuration, and any sizing has been conducted, an input file can be written for the resilience tool "engine." The input file is parsed by the resilience tool "engine" and a simulation is initiated.

During network simulation, operational components process load requests as best they can. Power is routed according to the dispatch algorithm of the network. At the end of each scenario's simulation, statistics are calculated related to requested load, achieved load, energy availability, and maximum downtime.

When the entire simulation of all scenarios completes, energy robustness, energy recovery, energy availability, and energy usage, and energy cost, for different loads during different DBTs can be calculated. Energy system recovery time is represented by maximum downtime in the tool. These metrics can be compared to goals to identify gaps or progress toward a target (see bottom and bottom-left of Figure 9). If sufficient progress has not been made, information from the last run can be used to enhance a subsequent architecture selection and configuration and the process can continue.

The resilience tool engine and process are designed to allow for the assessment of a given network configuration with explicitly defined components and an explicit dispatch methodology. The ultimate audience for the tool and process are master planners and energy managers. As such, a level of detail (fidelity) is trying to be achieved that is approachable by the target audience while also allowing for more depth and nuance than higher-level (i.e., less detailed) campus-level tools.

4.2. Multicriteria analysis of alternatives and scenario selection.

Analysis of the Base Case and alternatives produces quantitative results that allow a determination of how close the users were able to come to achieving their goals and objectives, and a comparison of the Baseline, Base Case, and alternatives using defined criteria. There may be additional conflicting qualitative and quantitative criteria (e.g., risk, safety, comfort, fuel availability, etc.) that can support decisions in defining the roadmap to achieving ultimate framing goals.

The decision criteria are not usually equally important. To support the installation's decision process, users must elicit relative weights for the different criteria from decision makers. This is not always an easy process, but it does encourage decision makers to reflect on how they make their decisions.

Multicriteria Decision Analysis (MCDA) can be used to create weighted decision models and support traceable decision processes that integrate quantitative and qualitative factors. MCDA allows for the selection of a reduced set of good, non-dominating alternatives to be presented to decision makers for final selection

4.3. Implementation.

4.3.1. Scope

The scope of the Energy Master Plan (EMP) can be broad; it may include new construction, demolition, and consolidation projects; energy supply; and energy distribution and energy storage components, including creative methods to build innovative site-to-grid arrangements that may provide grid stability or site resilience (Figure 10). An EMP is not limited to energy-related projects; it may include a spectrum of non-energy-related projects, including new building construction and demolition, utility modernization projects and non-energy-related measures to enhance the resilience of energy systems to DBTs, such as the elevation of energy equipment, construction of flood walls, burying of cables. In most of cases, an EMP covers multiple interrelated projects (Figure 11) where the outcome of one project or a group of projects influences one or more other projects (e.g., building efficiency improvements impact the size of required energy generation capacity; thermal energy supply to a new building requires installation of a pipe connection to existing district system; connection of additional buildings to a hot water district system allows for an increase of CHP base load). Therefore, selection of alternatives for an EMP shall be based on cost effectiveness of the entire EMP instead of individual projects that comprise the EMP. It is possible that some individual projects will not be cost effective when considered separately.

4.3.2. Life cycle cost analysis (LCCA)

One of the EMP alternatives, the Base Case, serves as a benchmark for LCCA of other alternatives. These alternatives might have different initial investment costs as well as different overall future cost savings, which could result in achieving better performance (e.g., greater energy use reduction, better environmental quality, and/or higher resilience of energy systems). LCCs typically include the following two cost categories: investment-related costs and capital expenditures (capex) and operating expenditures (opex).

Investment costs describe total expenses of the investment into (1) buildings and (2) energy supply and distribution systems. These costs include the planning, modeling, design, and implementation of new materials; and the replacement and disposal costs of replaced materials, including both material and labor costs. The number and timing of capital replacements or future investments depend on the estimated life of a system and length of the service period. Sources for cost estimates for initial investments can be used to obtain estimates of replacement costs and expected service lives. A good starting point for estimating future replacement costs is to use initial investment costs along with price escalation factors related to comparable building construction and energy supply investment cost indices.

4.3.3. Synergetic impacts

The determination of the investment costs must consider synergetic impacts that can be obtained from a holistic EMP approach. For example, one approach could be to combine demand reduction on building and energy supply level measures, which would in turn allow supply to be reduced as a result of the reduction in demand on the building level. Another approach could be to organize piping and cable configurations for thermal and electrical grids located in infrastructure trenches to reduce trenching costs, which can comprise over 50% of the total grid costs, depending on underground conditions.

Some standard building LCCA broadly considers many operational costs, most cost effectiveness calculations either on the building or the community level consider only energy cost benefits. Others compare scenarios which mainly considers capital costs of energy infrastructure and capital-intensive technologies characterized by economy of scale factors, which are important for integrating renewable energy.

However, ambitious energy investments often produce benefits beyond reduced energy consumption and peak demand shaving. Many of these additional benefits contribute to the objectives of organizations that implemented the projects and can have significant added value for those making investment decisions. Prior research [12] has investigated such benefits as the impact of increased thermal comfort on the productivity of the building occupants, or the willingness to pay increased sales prices or rental rates for higher performing buildings. Nevertheless, the monetization of non-energy benefits ("co-benefits") is still not broadly used on the building or building cluster level.

How to calculate risk and resilience costs and benefits: a long-duration power interruption and loss of thermal energy, especially in extreme climates, may significantly degrade regional and even national security (e.g., due to the loss of critical infrastructures or degrade critical missions at military bases). It can also affect health and safety of a community and even result in a loss of human life [13].

While the cost of a given resilience measure is well understood (e.g., the costs of labor and materials of "underground" power lines), the resulting benefits are more difficult to assess, particularly because of a lack of supporting data [14]. Although resilience has currently been acknowledged as a distinct benefit, it has not typically been quantified or valued.

Figure 10. Scope of the EMP.

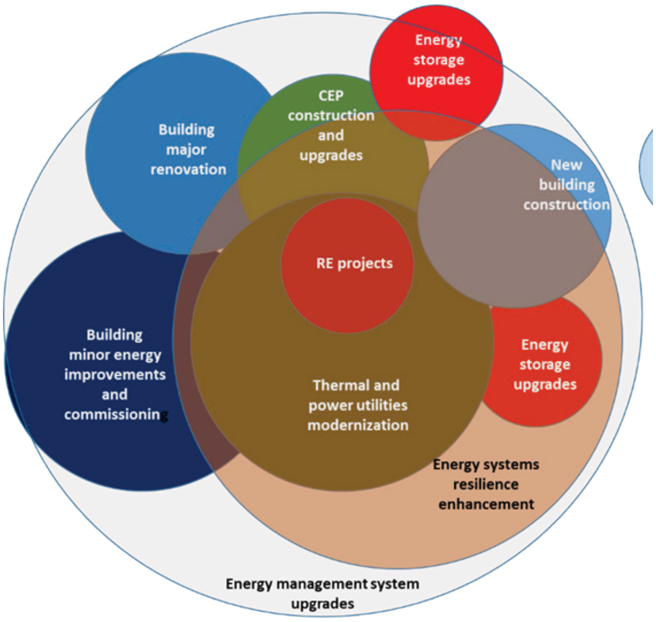


Figure 11. Interrelation of projects under EMP.

National Renewable Energy Laboratory (NREL) authors [15] argue that the types of data that would support the benefits associated with resilience measures are difficult to collect because of the time and types of events needed to demonstrate the value of resilience investments (e.g., 100-year flood events happen so infrequently that the benefits of mitigation measures associated with those events are difficult to quantify in a realistic time frame). Moreover, even if the health, safety, and economic impacts of a threat could be quantified, it is very challenging to translate those impacts into financial consequences, which will ultimately indicate to a given stakeholder whether a change in investment or operations is warranted.

The Guide describes LCCA two approaches to compare systems with different levels of energy systems resilience when benefits of resilience can (1) and cannot (2) be assigned.

4.3.4. Key Risk Factors

The decision-making process leading to EMP implementation is comparable to any other investment decision that requires variation analysis. The process assumes certain price, tax, and benefit value deviations. Analysis of a survey of project facilitators, Energy Service Companies (ESCOs), financiers, and insurance companies identified the following key risk factors: Capital costs, energy, maintenance and other life-cycle costs and energy savings. The Annex 73 Guide discusses how the design and execution of de-risking measures during different stages of the EMP development is crucial for the success of the EMP from the economic point of view. The detailed de-risking measures focus on the Key Risk Factors during the design and implementation phase of a project (investment and energy cost).

4.3.5. Business Models

Business Models are tools for the implementation of EMPs into reality such as energy supply, energy savings performance contracting, leasing etc. The Guide describes scopes and typical use cases of different business models and discusses pros and cons. In general, many public agencies and communities do usually provide insufficient funding and staff capacities to carry out complex EMPs over time. The use of well introduced business models may support especially the public sector to implement EMPs in a given budget and with guaranteed targets lined out in the Master Plan.

References

1.UNEP. *Energy Efficiency for Buildings*. www.studiocollantin.eu/pdf/UNEP%20Info%20sheet%20-%20EE%20Buildings.pdf.

2. Annex 51. 2014. *Energy Efficient Communities: Case Studies and Strategic Guidance for Urban Decision Makers. Project Summary Report*. https://iea-ebc.org/Data/publications/EBC_PSR_Annex51.pdf.

3. Zhivov A., M. Case, R. Liesen, J. Kimman, W. Broers. 2014. "Energy Master Planning Towards Net-Zero Energy Communities/Campuses." *ASHRAE Transactions*. 120(1).

4. Anders Dyrelund, Robert M. Neimeier, Hasmik Margaryan and Anders B. Møller. 2021. "Energy Master Planning for Resilient Public Communities – Best Practices from Denmark." *ASHRAE Transactions*. 127 (1).

5. Laxmi Rao (IDEA), Juan Ontiveros, Joseph Yonkoski, Joshua Wauthy, and Paul Holt. 2021. "Energy Master Planning for Resilient Public Communities – Best Practices from North American Universities." *ASHRAE Transactions*. 127(1).

6. *Energy Master Planning for Low Energy Resilient Public Communities – Case Studies*. https://annex73.iea-ebc.org/.

7. Danish Energy Agency. 1979. Danish Heat Supply Act. FT: 9469, 9508, 11597, 11773 A. 3417; B. 1515. Lov nr. 258 af 8. June 1979. https://www.folketingstidende.dk/samling/19781/lovforslag/L206/index.htm.

8. OASD. 2016. Installation Energy Plans. Memorandum. March 31. 2016.

9. Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency.

10. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources https://ec.europa.eu/energy/topics/renewable-energy/renewable-energy-directive/overview_en.

11. DoD 2020. DoD Memorandum. Metrics and Standards for Energy Resilience at Military Installations. Metrics and Standards for Assessment of Energy Resilience, Supporting Policy and Guidance and Associated Reporting Requirements. 15 February 2020.

12. Lohse R., A. Zhivov. 2020. Deep Energy Retrofit for Public Buildings. Business and Financial Models. Springer.

13. Viscusi, W. Kip, and Joseph E. Aldy. 2003. "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World." *Journal of Risk and Uncertainty* 27(1):5–76.

14. LaCommare, Kristina, Peter Larsen, and Joseph Eto. 2017. *Evaluating Proposed Investments in Power System Reliability and Resilience: Preliminary Results from Interviews with Public Utility Commission Staff*. Lawrence Berkeley National Laboratory. LBNL-1006971. https://doi.org/10.2172/1342947.

15. Murphy, Caitlin, Eliza Hotchkiss, Kate Anderson, Clayton Barrows, Stuart Cohen, Sourabh Dalvi, Nick Laws, Jeff Maguire, Gord Stephen, and Eric Wilson. 2020. *Adapting Existing Energy Planning, Simulation, and Operational Models for Resilience Analysis*. Golden, CO: NREL. NREL/TP-6A20-74241. https://www.nrel.gov/docs/fy20osti/74241.pdf.

Project Deliverables

1. Energy Master Planning for Low Energy Resilient Public Communities Guide.
2. Energy Master Planning for Low Energy Resilient Public Communities – Case Studies. https://annex73.iea-ebc.org/
3. Energy Resilience of Interacting Networks (ERIN) tool. https://annex73.iea-ebc.org/
4. Guide for Resilient Thermal Energy Systems Design in Cold and Arctic Climates. https://annex73.iea-ebc.org/
5. Guide for Resilient Thermal Energy Systems Design in Hot and Humid Climate. https://annex73.iea-ebc.org/

Project Participants

Country	Organization
Australia	University of Melbourne
	Ministry of Defense
Austria	AEE - Institut für Nachhaltige Technologien
	B.I.G. – Bundesimmobiliengesellschaft (LOI)
Denmark	Aalborg University
	Ramboll
	Ministry of Defense
	Danfoss
	EMD International
Finland	VTT Technical Research Centre of Finland
Germany	KEA Klimaschutz- und Energieagentur Baden-Württemberg
	GEF Engineering
	IREES - Institute for Resource Efficiency and Energy Strategies
	University of Applied Sciences Stuttgart
Norway	Norwegian University of Science and Technology
	SINTEF
UK	Ministry of Defense
USA	U.S. Army Engineer Research and Development Center Construction Engineering Research Laboratory
	U.S. Army Corps of Engineers, Protective Design – Mandatory Center of Expertise U.S. Army Corps of Engineers, Power Reliability Enhancement Program
	Fort Leonard Wood
	Sandia National Laboratories
	National Renewable Energy Laboratory
	SC-B Consulting
	Big Ladder Software
	The Holmes Engineering Group
	International District Anergy Association
	William B. Rose & Associates
	Oak Ridge National Laboratory
	AECOM
	ESG Energy Systems Group
	NAESCO - National Association of Energy Service Companies
	CDC- National Institute for Occupational Safety and Health

Publications

Laxmi Rao (IDEA), Juan Ontiveros, Joseph Yonkoski, Joshua Wauthy, and Paul Holt. 2021. "Energy Master Planning for Resilient Public Communities – Best Practices from North American Universities." *ASHRAE Transactions* 127(1).

Anders Dyrelund, Robert M. Neimeier, Hasmik Margaryan, and Anders B. Møller. 2021. "Energy Master Planning for Resilient Public Communities – Best Practices from Denmark." *ASHRAE Transactions* 127(1).

Anna Maria Fulterer, Ingo Leusbrock, Gert Widu and Dirk Jäger. 2021. *Energy Master Planning for Resilient Public Communities - Best Practices from Austria*.

Alexander Zhivov, William Rose, Raymond Patenaude, and William Warren. 2021. "Requirements for Building Thermal Conditions under Normal and Emergency Operations in Extreme Climates." *ASHRAE Transactions* 127(1).

Alexander Zhivov, Andrew Stringer, Michael Fox, John Benefiel, Patrick Daniels, and Todd Tarver. 2021. "Defining, Measuring and Assigning Resilience Requirements to Electric and Thermal Energy Systems." *ASHRAE Transactions* 127(1).

Lyle Axelarris, Aaron Cooke, Craig Fredeen, Robbin Garber-Slaght, Emmett Leffel, Lorne Ricketts, William Rose, John P. Zarling, and Alexander Zhivov. 2021. "Best Practices for HVAC, Plumbing and Heat Supply in Arctic Climates." *ASHRAE Transactions* 127(2).

Emily C. Winfield, Robin J. Rader, Alexander M. Zhivov, Thomas A. Adams, Anders Dyrelund, Craig Fredeen, Oddgeir Gudmundsson, and Brent Goering. 2021. "Best Practices for HVAC, Plumbing and Heat Supply in Arctic Climates." *ASHRAE Transactions* 127(1).

Emmett Leffel. 2021. "Building Enclosure Testing on Alaska Military Base Projects." *ASHRAE Transactions* 127(1).

Bjorn Oberg, Angela Urban, Emmette Leffel, Jonathan Goebel, Matt Perry, Dragos Vas, Dayne Broderson, Richard Liesen, Alexander Zhivov. 2021. "Thermal Energy System Resilience: Thermal Decay Test (TDT) in Cold/Arctic Climates, Part I Data Collection and Protocol." *ASHRAE Transactions* 127(2).

Richard J. Liesen, Brianna Morton, Brandy Diggs-McGee, and Alexander M. Zhivov. 2021. "Thermal Energy System Resilience: Thermal Decay Test (TDT) in Cold/Arctic Climates, Part II Modeling." *ASHRAE Transactions* 127(2).

Michael O'Keefe, Peter Ellis, Richard Liesen, Alexander Zhivov, and Anthony Latino. 2021. "A Tool for Modeling Energy and Resilience for Community-Scale Networks of Buildings and District Systems." *ASHRAE Transactions* 127(1).

Terry Sharp, Joergen Rose, Matthias Haase, Ruediger Lohse, Natasa Nord, Behzad Rismanchi, and Alexander Zhivov. 2020. "Energy Master Planning: Identifying Framing Constraints that Scope Your Technology Options." *ASHRAE Transactions* 126(1).

Robert F. Jeffers, Amanda Wachtel, Avinash Srivastava, Calum Thompson, Alexander Zhivov, Patrick Daniels. 2020. "Integration of Resilience Goals into Energy Master Planning Framework for Communities." *ASHRAE Transactions* 126(1).

Angela Urban, Elisabeth Keysar, Alexander Zhivov, Kathleen Judd, Avinash Srivastava, Calum Thompson, Nicholas Josefik, and Michael Case. 2020. "Energy Master Planning for Resilient Public Communities – Best Practices from US Military Installations." *ASHRAE Transactions* 126(1).

Annette Roser, Karin Schakib-Ekbatan, Verena Weiler, Ursula Eicker, and Rüdiger Lohse. 2020. "Energy Master Planning for Resilient Public Communities – Best Practices from Germany." *ASHRAE Transactions* 126(1).

Saeid Charani Shandiz , Behzad Rismanchi, and Greg Foliente. 2020. *Energy Master Planning for Net-Zero Emission Communities: State of the Art and Research Challenges*. Elsevier: Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2020.110600.

Saeid Charani Shandiz, Greg Foliente, Behzad Rismanchi, Amanda Wachtel, and Robert F. Jeffers. 2020. *Resilience Framework and Metrics for Energy Master Planning of Communities. Elsevier: Energy*. www.elsevier.com/locate/energy.

Alexander Zhivov. 2021. "Parameters for Thermal Energy Systems Resilience." E3S Web of Conferences 246, 08001 (2021). Cold Climate HVAC & Energy 2021. https://doi.org/10.1051/e3sconf/202124608001.

Bjorn Oberg, Angela Urban, Emmett Leffel, Jonathan Goebel, Matthew Perry, Dragos Vas, Dayne Broderson, Richard Liesen, and Alexander Zhivov. 2021. "Analyzing the Factors that Effect Maximum Time to Repair Thermal Energy Systems in Cold/Arctic Climates." E3S Web of Conferences, 08002 (2021). Cold Climate HVAC & Energy 2021. https://doi.org/10.1051/e3sconf/202124608002.

M. Case, R. Liesen, M. Swanson, J. Yu, and A. Zhivov. 2015. "Integration of Master Planning and Energy Planning: From Detailed to Conceptual Analysis." *ASHRAE Transactions* 121(1).

Alexander M. Zhivov, William B. Rose, Raymond E. Patenaude, and W. Jon Williams. 2021. "Requirements for Building Thermal Conditions under Emergency Operations in Cold Climates." E3S Web of Conferences, 08003 (2021). Cold Climate HVAC & Energy 2021. https://doi.org/10.1051/e3sconf/202124608003.

Emily C. Winfield, Robin Rader, Alexander Zhivov, Anders Dyrelund, Craig Fredeen, Oddgeir Gudmundsson, and Brent Goering. 2021. "HVAC Best Practices in Arctic Climates." E3S Web of Conferences, 08004 (2021), Cold Climate HVAC & Energy 2021. https://doi.org/10.1051/e3sconf/202124608004.

Andrey Strongin and Alexander Zhivov. 2021. "Energy Efficient Air Curtains for Industrial Gates in Cold Climates." E3S Web of Conferences, 08005 (2021), Cold Climate HVAC & Energy 2021. https://doi.org/10.1051/e3sconf/202124608005.

Oddgeir Gudmundsson, Anders Dyrelund, and Jan Eric Thorsen. 2021. "Comparison of 4th and 5th Generation District Heating Systems." E3S Web of Conferences 246, 09004 (2021), Cold Climate HVAC & Energy 2021. https://doi.org/10.1051/e3sconf/202124609004.

Abbreviations

Abbr.	Term
CHP	Central Heating Plant
DBT	Design-Basis Threats
DoD	U.S. Department of Defense
EA	Energy Availability
EBPD	Energy Performance of Buildings Directive (EU)
EMP	Energy Master Plan
EQ	Energy Quality
ER	Energy System Robustness
ERA	Energy Resilience Analysis
ERIN	Energy Resilience of Interacting Networks
ESCO	Energy Service Companies
GHG	Greenhouse gas
HVAC	Heating, Ventilating, and Air-Conditioning
IEA	International Energy Agency
LCCA	Life Cycle Cost Analysis
LCOE	Levelized Cost of Electricity
MCDA	Multicriteria Decision Analysis
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Cooperation and Development
PREP	Power Reliability Enhancement Program
PV	Photo voltaic
R&D	Research and Development
SCADA	Supervisory Control And Data Acquisition
SMPL	Simple Master Planner

IEA and EBC

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international cooperation among the 29 IEA participating countries and to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA coordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the IEA Energy in Buildings and Communities (IEA EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities through innovation and research. (Until March 2013, the IEA EBC Programme was known as the IEA Energy in Buildings and Community Systems Programme, ECBCS.)

The R&D strategies of the IEA EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. These R&D strategies aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five areas of focus for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)

Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterization Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimized Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Public Communities
Annex 74: Energy Endeavour
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: EBC Annex 76 / SHC Task 59 Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: EBC Annex 77 / SHC Task 61 Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling of Buildings
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

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EBC is a programme of the International Energy Agency (IEA)