

Towards Net Zero Buildings

The Investment Case

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Welcome and Context of Research

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Dear Reader,

This report is complementary to our recently released flagship report, “Decarbonizing Buildings to the Benefits of Consumers and System Operators”, (Minier, 2024). A key originality of this report was the in-depth exploration of decarbonized buildings through the deployment of a digital and low-carbon technology package, consisting of a heat pump, rooftop solar photovoltaic (PV), a stationary battery, and a building (or home) energy management system, across a variety of building types, ages and geographical contexts (with different electricity dynamic tariffs, capital costs, sunlight patterns, etc.). Our study examined energy bill reduction, CO2 emissions reduction, and investment payback for decarbonization technologies, along with their impact on peak load. A key finding revealed that optimizing technology sizing could significantly reduce energy bills, but often required substantial initial investments, such as large battery installations.

This new study explores the optimization of system sizing to achieve specific profitability targets while maintaining substantial decarbonization and cost reduction benefits. The research primarily concentrates on two key aspects: developing an effective analytical tool to visualize the range of viable investment options, and determining appropriate profitability targets tailored to different project types and investor profiles, considering their respective hurdle rates.

We selected a simple graphical tool combining three project key performance indicators (KPIs), which allows us to visualize the impact of system sizing changes on the economics of chosen use cases (profitability of the investment, energy bill variation), and CO2 emissions variation.

Exhibit 1. Illustrating how the system sizing can be optimized to reach a profitability target while not compromising CO2 emissions or energy bill reduction. (Each dot represents a possible PV-Battery system sizing).

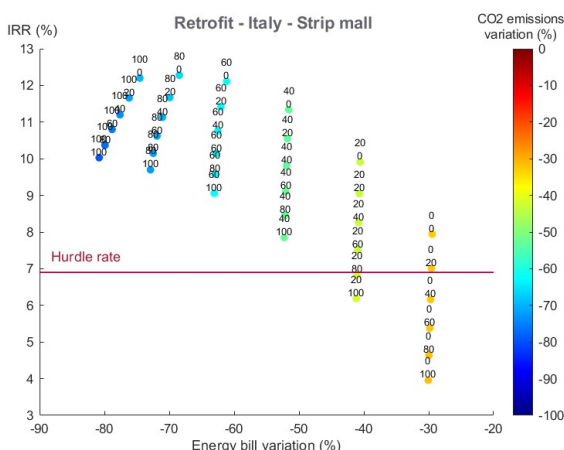


Exhibit 1 illustrates this with the Internal Rate of Return (IRR) as the chosen profitability KPI, the red line representing the minimum profitability level to be achieved (hurdle rate) according to the investor criteria.

When deploying a decarbonization package, estimating relevant hurdle rates is key to ensuring a fair profitability assessment. Our takeaway is that it is a complex task as, depending on the practice, project risks may be factored into the project hurdle rate and/or cash flows.

Given the diversity of primary or combined objectives, there is no “one investor” profile. For example, there is nothing in common between considering:

- A city investing in a public hospital,
- A citizen investing into the renovation of his privately owned house,
- A Real Estate investment for lending an office.

The overall equation of an investor may cover one or all the following objectives: profitability, energy bill reduction, CO2 emission reduction, maximum peak load, maximum CAPEX, expected green rental or green asset premium, or other non-financial value (e.g., welfare, brand image). Also, profitability (and hurdle rates) may not be the primary criteria in some investment cases.

For instance:

- A company committed to decarbonizing its building portfolio “whatever it costs” may prioritize environmental impact over financial returns.
- An individual investor in new construction may be more concerned with the mortgage rate for the house construction rather than a specific hurdle rate.

To reflect real-world scenarios, we applied our graphical analysis tool to five distinct investment cases across various building segments, encompassing different investor types and specific hurdle rates. This diverse selection highlights the intricacy of investment decisions and emphasizes the necessity for a sophisticated approach that integrates both financial and non-financial considerations when evaluating project viability and attractiveness.

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Key insights

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Looking at the combined overall profitability, energy bill reduction, and CO2 emissions reduction for an **illustrative** dual IRR-bill optimization strategy (Exhibit 2), our main findings are the following:

• **Investments are valid in almost all cases, halving energy bills and CO2 emissions on average and at reasonable payback periods.**

• Maximizing photovoltaic system size is a strategic approach to maintaining financial performance while optimizing energy generation: The maximum PV size is selected in most use cases, as increasing the PV size generally contributes to an IRR that increases or remains stable, in addition to reducing bills.

• Battery investments demonstrate selective financial viability contingent upon specific market and tariff conditions: The battery is an attractive investment in about 40% of all use cases, yielding a good IRR driven by notable bill reductions. This is primarily due to specific grid tariffs making the battery particularly relevant.

• Strategic system sizing can yield significant payback improvements with limited impacts on other criteria: It is possible to improve project profitability compared to a sizing strategy only optimizing the energy bill while not being too detrimental to CO2 emissions reduction and/or energy bill reduction. This is evidenced by an average decrease in the simple payback period of 5 years for retrofit and new construction projects.

Setting a hurdle rate for sustainable investments has been highly controversial over the last two decades, and financial markets have not yet factored it in. Still, we advocate for a lower cost of capital for ESG-related projects, higher asset valuations for sustainable buildings, and improved cash flow projections for green investments. Therefore, these adjustments should significantly improve payback periods, making decarbonization more financially attractive.

Finally, we examine the potential impact of the low-carbon package on grid burden in retrofit use cases:

- Consistent with prior research, import peak issues arising from battery operation can be effectively addressed by incorporating a grid power limit constraint within the battery dispatch algorithm.
- Similarly, import peak issues associated with heat pump operation can be mitigated using a grid power limit constraint battery. However, in a small subset of retrofit cases (10 out of 63, primarily affecting residential properties), complete suppression of these issues is not feasible.

Overall, this work lays the groundwork for more informed decisions for decarbonization investments in buildings. We hope this work will catalyze confidence in building sector decarbonization investments and stimulate further research and discussion in this critical area.

Candela Utrilla Bustamante
Energy Management Simulation, AI Hub, Schneider Digital

Exhibit 2. Internal rate of Return and simple payback¹ for the implemented dual sizing strategy (IRR-bill), the 126 use cases under study

		SIZING RULE "MIXED IRR - BILL"																	
		RETROFIT									NEW CONSTRUCTION								
SIMPLE PAYBACK (YEARS)		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S
		Legend: <= 10 (Green), > 10 & < 30 (Orange), = 30 (Red)																	
Private investor	Large office	27	24	15	20	17	17	22	10	30	9	19	19	14	11	13	17	7	20
	Small hotel	10	13	10	11	10	7	14	7	24	7	11	9	10	8	7	12	8	19
	Strip mall	10	10	8	11	8	6	13	7	18	6	6	3	7	6	3	7	5	17
Househ.	Mid. apart.	25	9	8	9	9	9	15	10	28	7	5	4	5	6	5	5	4	16
	Single house	18	8	7	9	8	9	11	10	28	9	5	5	5	6	5	6	7	19
Public investor	Hospital	18	10	6	9	7	7	12	7	16	11	10	7	9	7	7	12	6	16
	Sec. school	30	18	12	17	13	14	21	10	23	8	14	14	11	8	11	12	7	19

		SIZING RULE "MINIMUM BILL"																	
		RETROFIT									NEW CONSTRUCTION								
SIMPLE PAYBACK (YEARS)		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S
		Legend: <= 10 (Green), > 10 & < 30 (Orange), = 30 (Red)																	
Private investor	Large office	27	26	27	28	28	23	30	10	30	11	23	30	25	26	24	30	8	26
	Small hotel	11	13	17	18	13	9	22	7	26	7	11	13	12	11	7	13	8	21
	Strip mall	10	10	11	12	9	6	16	7	20	6	9	8	8	6	5	8	5	20
Househ.	Mid. apartment	30	29	13	30	23	14	30	20	30	13	26	8	24	12	10	10	8	30
	Single house	23	17	11	18	18	19	21	19	30	11	8	8	13	9	16	9	11	30
Public investor	Hospital	25	12	14	12	11	11	24	8	23	13	11	18	12	13	11	24	7	20
	Sec. school	30	18	16	18	16	15	24	10	25	8	15	14	11	9	13	13	7	21

¹ The simple payback is the profitability KPI used in the precedent report and kept here for comparison purpose. This KPI is less accurate than the IRR, since the cashflows used in its calculation are not discounted (consequently, it does not consider the time value of money, nor the inflation). Note that the provided simple paybacks are upper bounded at the lifetime of the project (30 years).

Foreword

Dr Jan Rosenow, Vice President, and European Program Director
Regulatory Assistance Project (RAP)



The challenge of decarbonizing the building sector is both pressing and complex. Buildings account for a substantial share of global emissions, yet the sector remains one of the most fragmented and difficult to transform.

This report offers an important and timely contribution to addressing these challenges, providing a practical framework for optimizing investment in building decarbonization while balancing profitability, energy cost reduction, and emissions reduction.

Through innovative use of key performance indicators (KPIs), this study introduces a tool to help stakeholders visualize the economic and environmental impact of system sizing decisions. By exploring a diverse set of building types, geographies, and investor profiles, the authors highlight the nuanced trade-offs required to achieve decarbonization goals.

The insights are compelling: maximizing photovoltaic (PV) capacity consistently enhances both profitability and energy savings, while battery investments depend heavily on contextual factors, such as grid tariffs and electricity pricing dynamics.

One of the report's key strengths is its recognition of the diversity among investors. From municipalities decarbonizing public infrastructure to homeowners retrofitting private properties, each investor type brings unique objectives and constraints. By tailoring the analysis to specific use cases and hurdle rates, this work equips stakeholders with actionable insights, making the case for decarbonization investments more transparent and accessible.

Equally significant is the focus on grid impacts. As the findings demonstrate, operational adjustments can mitigate challenges like import peak issues from battery and heat pump operation. However, as the authors rightly note, certain retrofit scenarios—particularly in the residential sector—present residual challenges, underscoring the need for continued innovation and policy support.

What makes this report particularly valuable is its balanced perspective. While it highlights opportunities to improve profitability and reduce payback periods, it does not shy away from addressing the complexities of financing and decision-making in this space.

As the authors point out, financial markets have been slow to adapt to the realities of decarbonization. Lowering the cost of capital, recognizing the asset value of green investments, and improving cash flow structures will be essential to driving widespread adoption.

This report represents a critical step forward, not only in providing technical analysis but also in fostering greater confidence among investors and policymakers.

By combining rigorous data analysis with practical recommendations, it offers a pathway to scaling up decarbonization efforts in the building sector—a sector whose transformation is essential to achieving global climate goals.

It is my hope that this work inspires meaningful action, sparks new discussions, and drives further innovation in the pursuit of a sustainable future.

The journey to decarbonize buildings is not an easy one, but with tools like those presented in this report, it becomes a more achievable—and rewarding—endeavor.

Dr Jan Rosenow,
Vice President, and European Program Director
The Regulatory Assistance Project (RAP)



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Part I: Problem Statement

This report aims to contribute to the growing field of building decarbonization by proposing a simple tool to visualize the viability of decarbonization investments and select an optimal sizing.

Given the potential for significant energy savings, electrification, and digitization in the building sector, it is interesting to identify investment opportunities that align with environmental (CO2 emissions reduction) and financial goals (profitability, operational expenditure savings, ...).

This research takes its roots in our previous study on Buildings & Cities: "Decarbonizing Buildings to the Benefits of Consumers and System Operators" (Minier, 2024).

This report analyzed the impact of four low-carbon technologies

- Building Management Systems (BMS), heat pumps, Photovoltaic systems (PV), and batteries - in 126 different use cases covering multiple geographies, building segments, and ages. In each use case, the PV system and the battery were sized to minimize the annual energy bill of the building.

Our research demonstrated that building decarbonization can be achieved cost-effectively while enhancing resilience. The integration of electrified heating systems, Building Management Systems (BMS), on-site solar generation, energy storage, and intelligent digital management yield substantial advantages for building owners and occupants, particularly when optimizing for energy cost reduction. These findings are summarized in Exhibit 3, which illustrates the potential benefits of this comprehensive approach to building energy systems.

Exhibit 3. Decarbonized building performance synthesis in the case of an energy bill minimization strategy.

	CO2 emissions	Energy bill	Simple payback ²	Burden of electrification ³
Commercial buildings (Office, Hospital, Hotel, School, Mall)				
Retrofit	CO2 savings range within -15% - 80% depending on segments	Energy bill savings range within -15% - 80% depending on segments	Wide array of paybacks from 5 to 30 years depending on segments	No load above subscribed power except for a few cases, incl. Denmark as a special case
New build	(Office, Hospital, Hotel within -15%--55%, School and Mall within -50%--80%)	(Lower for Office, Hospital, Hotel, higher for School and Mall)	Mostly between 5 and 15 years (worse for Large Office and USA South)	Taken into account by grid operator at construction (but improved case vs Retrofit) No issue for behind-the-meter electrical distribution infrastructure
Residential buildings (single family households and multi-dwellings)				
Retrofit			Paybacks above 15 years	Load above subscribed power in almost all the cases in both single house and midrise apartment
New build	CO2 savings range within -50% - 70%	Energy bill savings range within -60% - 90% depending on segments	Paybacks in the 10–15-year range (worse for USA South and apartment segment in France and Eastern China)	Taken into account by grid operator at construction (but improved case vs Retrofit esp. In multi-dwelling) No issue for behind-the-meter electrical distribution infrastructure

²The simple payback is the profitability key performance indicator used in the precedent report. The cashflows used in its calculation are not discounted (consequently, it does not consider the time value of money, nor the inflation). Note that the simple paybacks calculated by the used simulation framework are upper bounded at the lifetime of the project (30 years).

³When incorporating an additional power limit constraint into the simulation, 75% of retrofit use cases had no peak issue in the studied scope PV panels and battery sizes.

Going beyond pure bill optimization

Optimizing solely for energy bill reduction can be appropriate in certain scenarios. For instance, when a prospective homeowner considers implementing a comprehensive decarbonization package—including heat pumps, home controls, rooftop photovoltaics, and stationary batteries—the additional capital expenditure is relatively minor compared to the overall construction costs. In such cases, the focus may justifiably shift towards the operational cost savings these technologies can provide.

However, it is crucial to recognize that investors have diverse objectives and priorities. The decision-making process often encompasses multiple criteria beyond mere operational expenditure savings. These may include profitability targets, CO2 emissions reduction goals, capital and replacement cost constraints, peak load management, potential green premiums, and even intangible factors such as occupant welfare or brand image.

There are a few similarities between how a homeowner, a private company, and a city are considering their investments, as shown in these examples:

- First, private companies consider the time value of money and look at the profitability of the projects. But other objectives may also be taken into consideration:
 - o A private company seeking to renovate its office building is often driven by cost-saving and sustainability goals. Energy-efficient upgrades can reduce operational expenses while enhancing the company's carbon footprint and environmental image.
 - o A Real Estate developer for a newly built multi-dwelling green building aims to maximize return on investment. Energy-efficient features and renewable energy installations can differentiate the property in a competitive market, attract environmentally conscious tenants, and potentially increase rental income.
- Second, citizens may prioritize personal comfort, increased property value, and benefit from potential government incentives. Energy-efficient improvements can offer long-term savings on utility bills and contribute to a more sustainable lifestyle.
 - o When renovating their home, the usual thinking is to look at simple payback as a straightforward metric that helps individuals assess the time it takes for an investment to break even. Simple payback does not consider the time value of money or cash flows beyond the payback period.
 - o For a new building, the approach may be even more straightforward as a low-carbon equipment package can be added to the construction bill of material, only accounting for a small part of it, impacting the mortgage rate marginally.
- Third, a municipality investing in a public hospital must consider cost-effectiveness (and therefore profitability), but it is motivated by public health concerns, energy security, and community well-being. Decarbonizing such a critical infrastructure can ensure a reliable energy supply and improve the quality of care.

This report proposes substituting the sizing strategy used in our previous research, based on pure bill minimization, with a comprehensive sizing approach based on a multi-criteria assessment. This allows us to have a sound analysis of all the investment options, adaptable to the specificities of each investor.

The proposed approach is based on a tool allowing to visualize what each solution delivers for the variables of interest (e.g., profitability, CO2 reduction, etc.) when looking at the entire PV and battery sizing space. It reveals whether a solution provides adequate values for all the variables of interest and, if not, enables the investor to quantify the concessions.

Report organization

Following this introductory Part I, the report is organized as follows.

In Part II we outline the methodological approach of this research.

- We first summarize the methodology followed in our prior research, which is partially used in this report. Then, we introduce a simple yet effective visualization tool: the scatter plot representing the primary outcomes obtained with the various PV and battery sizes evaluated in each use case. This allows for a visual assessment of the trade-offs between CO2 emissions, energy bills, and profitability, which can be helpful for investors when deciding on the final PV and battery sizing.
- We justify using the internal rate of return (IRR) as the profitability key performance indicator (KPI) before explaining the critical role of the hurdle rate, which represents the minimum rate of return required for each project to be considered viable. Finally, we derive the best estimates of hurdle rates for some specific investor profiles operating in a set of building segments.

Part III focuses on the practical usage of the developed scatter plot for the PV and battery sizing process for the previously selected investor profiles. By examining these cases in detail, we can identify unique challenges and opportunities associated with the diverse types of decarbonized building projects.

In Part IV, we complement this analysis with a mapping of the characteristics of 126 use cases for a specific optimization strategy and then comparing them to the ones of the previous research.

Part V summarizes our research's key findings and conclusions and points out the effort underway to improve financing conditions for decarbonization projects.

Although not the focus of this research, we include a Grid burden analysis in the Annex.

Part II: Methodological approach

In this Part II of the report, we outline the methodological approach of this research. First, we summarize the methodology followed in our prior study and partially use it in this report. Then, we introduce a simple visualization tool: the scatter plot, which represents the primary outcomes obtained with the various PV and battery sizes evaluated in each use case. Finally, we show how to use the tool when incorporating the hurdle rate of a given project and explain how we select hurdle rates for analyzing a few illustrative cases in Part III.

Methodological ground

This research is based on the results of the previous report of our series Buildings & Cities, “Decarbonizing Buildings to the Benefits of Consumers and System Operators” (Minier, 2024), which analyzes the impact of a package of low-carbon technologies on 126 building use cases.

Scope

The package of low-carbon technologies includes a heat pump, a building management system (BMS)⁴, a rooftop photovoltaic system (PV) and a stationary battery⁵.

The 126 use cases are built by pairing seven building segments, two building ages (for retrofit or new construction), and nine geographical locations. Each use case is associated with a rich parameter set, described in Exhibit 4.

More details regarding all these parameters can be found in the Annex of our previous research (Minier, 2024).

The impact of the low-carbon package is assessed in terms of energy bill reduction (i.e., electrical and gas bill reduction), CO₂ emissions reduction, and profitability.

To evaluate the profitability, the report considers both the costs associated with the low-carbon technology package and the savings yielded by it (i.e., the energy bill reductions)⁶.

It's important to note that, while often available, incentives that could reduce capital costs are not considered in the analysis. Also, projects and lifecycle costs are disregarded, with the exception of battery replacement costs when applicable.

Exhibit 4. Synthetic view of the use cases addressed and the parameters used.

USE CASES	<p>7 building segments</p> <ul style="list-style-type: none"> • Single house (220m², 2 floors) • Midrise apartment (3100m², 4 floors) • Large office (46300m², 12 floors) • Hospital (22400m², 5 floors) • Small hotel (4000m², 4 floors) • Retail strip mall (2100m², 1 floor) • Second. school (19600m², 2 floors) <p>2 building ages</p> <ul style="list-style-type: none"> • Old ('Retrofit'), corresponding to 1980/2006 buildings • New construction, corresponding to 2019/2021 buildings <p>9 geographies</p> <p>North America:</p> <ul style="list-style-type: none"> • Canada (Ontario province) • USA Northeast (Maryland) • USA West (California) • USA South (Florida) <p>Asia:</p> <ul style="list-style-type: none"> • Eastern China (Zhejiang province) <p>Europe:</p> <ul style="list-style-type: none"> • France • Italy • Spain • Denmark 	<p style="text-align: center; font-weight: bold; font-size: 2em;">TECHNICAL PARAMETERS</p> <p>Annual thermal and electrical consumption profiles (15-min steps) per load type (e.g., lighting, heating, ventilation, etc.), assuming gas-based heating systems and electrical cooling systems. Vary by geography, building segment and age.</p> <p>Eu.BAC coefficients (to model energy savings from BMS). Vary by load type, building segment and age.</p> <p>Annual coefficient of performance (COP) profiles (to model the substitution of heating and cooling equipment by a heat pump). Vary according to the temperature profiles of each geography.</p> <ul style="list-style-type: none"> • Heat pump sized according to the heating and cooling needs of each use case. <p>PV system with annual irradiation profiles varying by geography.</p> <ul style="list-style-type: none"> • Six PV sizes tested. Maximum PV size based on the roof space available in each building segment and age. <p>Battery with 90% roundtrip efficiency, 0.5 C-Rate and life of 3650 full equivalent cycles.</p> <ul style="list-style-type: none"> • Six battery sizes (i.e., capacities) tested. Maximum battery size equal to 25% of the average daily electrical consumption of each use case (after installation of heat pump and BMS). <p>Grid CO₂ content varying by geography (but not in time), constant gas CO₂ content .</p>
	<p style="text-align: center; font-weight: bold; font-size: 2em;">COST PARAMETERS</p> <p>BMS: capital cost (USD/m²) considered, varies by building segment.</p> <p>Heat pump: capital cost (USD/kW thermal) considered, same across all use cases.</p> <ul style="list-style-type: none"> • In new construction, capital cost of conventional heating and cooling systems deducted. <p>PV system: capital cost considered (USD/kW), varies by geography, building segment and age.</p> <p>Battery: capital cost considered (USD/kWh), varies by geography, building segment and age. Replacement cost also considered, equal to capital cost (the number of replacements depends on the battery wear, inferred from simulation results)</p> <p>Electricity tariff: complex tariff considered, varies by building segment and geography. May include fixed, energy, and power components.</p> <p>Gas tariff: Simple tariff considered (USD/kWh thermal) varies by geography.</p> <p>30 years of project lifetime considered for profitability calculations.</p> <ul style="list-style-type: none"> • No salvage value considered for the BMS, the heat pump or the PV system. • Salvage value considered for the battery (depending on the level of wear of the last battery replaced) 	

⁴In the case of residential segments (i.e., single house and midrise apartment), the term “home management systems” (HEMS) should be used instead of “building management systems”. However, for the sake of simplicity, the second term will be used all throughout the report, both for commercial and residential building segments.
⁵The combination of the PV system and the battery is often denoted as “microgrid” in this report.
⁶In this regard, it is important to highlight that the scope of the heat pump investment changes according to the age of the building. In retrofit use cases, it is supposed that the building already exists, and that we are assessing the opportunity of exchanging the existing heating and cooling system by a heat pump. Consequently, the complete capital cost of the heat pump is considered. On the contrary, in new construction use cases it is supposed that the building has not yet been constructed and that we are evaluating the opportunity of installing a heat pump versus the opportunity of installing a conventional heating and cooling system. This is why the capital cost of the conventional system is deducted from the heat pump capital cost.

Simulation tool

The study was conducted with proprietary Schneider Electric's Energy Management Simulation Framework (EMSF), a powerful and flexible simulation platform based on MATLAB/Simulink. This platform allows for performing time-domain simulations of environments where an energy management process is at stake. Typically, it is very well suited to model an environment with an initial electrical and thermal consumption (such as a building) where a microgrid is installed. The microgrid may include various distributed energy resources (e.g., diesel generator, photovoltaic system, battery, etc.). If it consists of a dispatchable resource, such as a battery, a dispatch algorithm is required to control it, which is also provided by EMSF.

Exhibit 5 presents the operation principle of EMSF for the microgrid application.

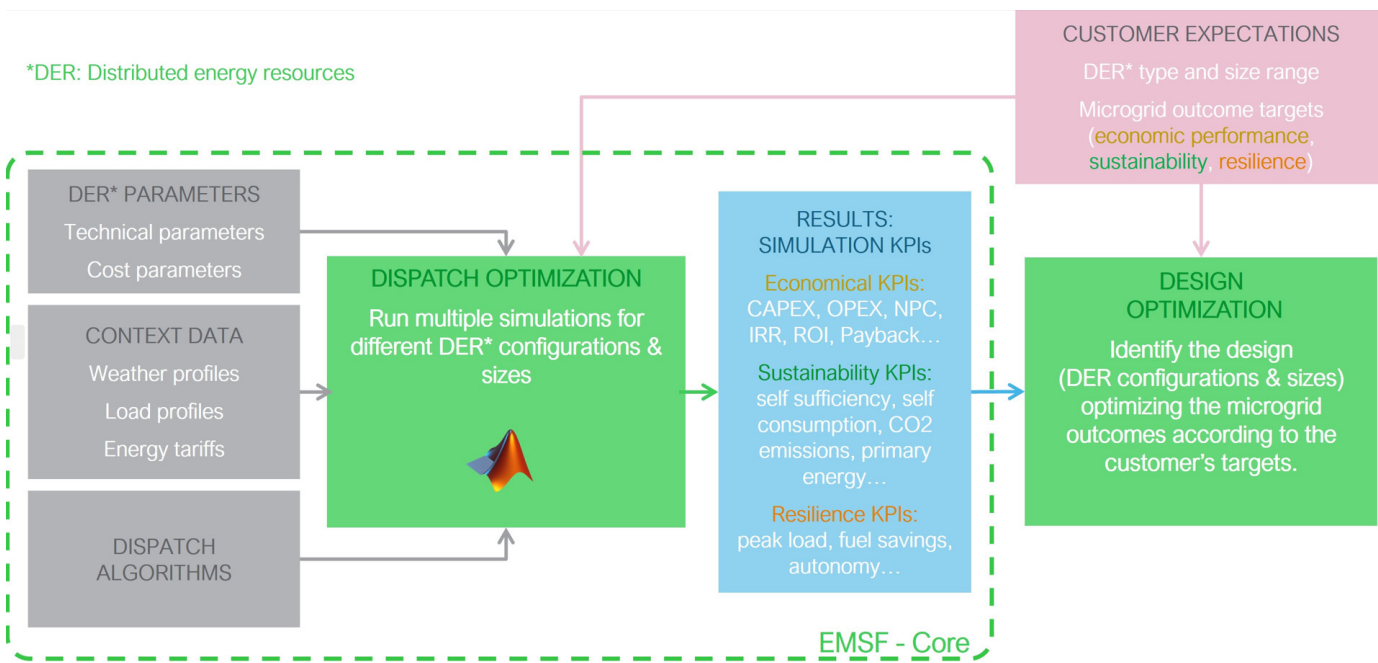
There are two distinct optimization stages:

- **Dispatch optimization:** A time-domain simulation is executed for a given microgrid design (i.e., a specific configuration and sizing of the distributed energy resources). The simulation uses multiple data sources and, if necessary, a dispatch algorithm for the dispatchable resources. The outcomes of this stage are the time series resulting from the simulation and a comprehensive set of key performance indicators (KPIs).
 - Note that the dispatch optimization stage is repeated for every microgrid design that needs to be evaluated (for example, every combination of PV and battery sizes that needs to be tested).
- **Design optimization:** The best design is selected according to the customer's targets using the results obtained for all the microgrid designs assessed.

Workflow

Given the operation principle of EMSF, the following workflow was implemented for each use case:

Exhibit 5. EMSF operation principle for microgrid applications.



1. Pre-processing:
 - The building's thermal and electrical load profiles are modified to model the installation of a BMS and the substitution of heating and cooling equipment by a heat pump.
 - Note that a single BMS and heat pump size is selected for each use case (unlike for the PV system and the battery, where multiple sizes are tested, as explained below)
2. Dispatch optimization for 6 PV sizes x 6 battery sizes (i.e., 36 simulations):
 - One-year simulations with 15-minute time steps.
 - The maximum tested PV size depends on the available roof space of each use case. For retrofit use cases, the available roof space goes from 10% to 50% of the total roof space, depending on the building segment. For new construction, the available roof space for PV is assumed to be 70% of the total roof space for all segments.
 - The maximum tested battery size equals 25% of the use case's average daily electrical load (after implementing the BMS and the heat pump).
 - The dispatch is achieved using a Model Predictive Control (MPC) algorithm that calculates the setpoints of the battery using forecasts of the energy costs, the uncontrollable building loads, and the PV production. Its objective function targets the minimization of both the energy and power components of the electrical bill⁷.
3. Design optimization:
 - Among the 36 microgrid sizes, the one exhibiting the lowest bill was selected⁸.

As discussed in the introduction, using a minimum bill strategy for design optimization is a limiting approach that does not fit the requirements of typical investors who often want to optimize multiple criteria. Therefore, this report explores a new design optimization approach. It consists of a multi-criteria assessment, for which we have designed a visualization tool that allows us to visualize the entire sizing solution space and how it affects three key criteria.

⁷ It is possible to modify the objective function of the used MPC algorithm, so that the battery also aims for the compliance of grid power limits (i.e., that the power imported or exported to/from the grid respects a certain threshold). This option was not used in the main simulations of the previous report, which are also the main simulations that will be used in this report. However, to address the grid burden issue, the simulations of the retrofit use cases were repeated with a grid limit option activated. The results of those simulations are discussed in the Annex "Grid".

⁸ In the use cases for which sellback is authorized, we excluded all the microgrid sizes that make the annual sales of exported energy exceed the annual costs of imported energy. This study is focused on optimizing the energy use within a building and does not consider the situation where a building becomes a net producer site (i.e., PV farm-like).

Towards Net Zero Buildings - The Investment Case

A tool to analyze the sizing solution space.

The tool facilitating the design optimization stage depicts all the tested PV and battery sizes in a use case and shows how these affect three potentially interesting criteria for an investor in low-carbon technologies: energy bill reduction, CO2 emissions reduction, and profitability.

Choice of profitability KPI

Several KPIs are traditionally used to measure a project's profitability, such as the internal rate of return (IRR), the net present cost (NPC), or the discounted payback. Their calculation is similar and includes adding discounted costs and earnings during a project's lifetime. The formulas used to calculate these KPIs are gathered in the Annex "Basic notions on profitability."

Although the three KPIs above measure a project's profitability, they do not provide the same information. Consequently, each investor must choose the KPI that best suits his objectives. It is also possible to use several of them in a complementary way.

For this study, we use the IRR as the paramount profitability KPI.

Two reasons justify this choice:

- First, one of the main objectives of this report is to illustrate the high sensitivity of profitability to the choice of hurdle rate. In this sense, neither the NPC nor the discounted payback is practical since their calculation uses the hurdle rate as input data, and they must be recalculated if the hurdle rate is modified. In contrast, calculating an IRR does not require the prior definition of a hurdle rate. Still, the IRR obtained is compared with the hurdle rate a posteriori (an IRR greater than the selected hurdle rate means the project is viable, and vice versa).
- Second, the IRR is normalized by expenditure size and can be used to compare investment opportunities of different types and sizes. This makes the IRR particularly suitable for this report, where the various building segments assessed require vastly different investments.

Choice of the visualization tool

We chose a scatter plot for depicting all the tested PV and battery sizes in a use case, as exemplified in Exhibit 6 in which:

- Each dot represents a microgrid design (i.e., PV and battery size), with two numbers on top of each dot:
 - o The top number is the PV size, a percentage of the maximum tested PV size in the use case.
 - o The bottom number is the battery size as a percentage of the maximum tested battery size in the use case.
- Dots are spatially arranged according to the energy bill variation and the IRR achieved with the corresponding microgrid size. It is worth noting that the IRR calculated by EMSF is lower bound at 0.
- Dot color is used to display the CO2 emissions variation (only emissions related to gas consumption and grid energy consumption; embodied emissions are not considered)
- Finally, the three KPIs displayed are relative to the baseline of each use case (i.e., the state of the building before the implementation of the BMS, the heat pump, or the microgrid)⁹.

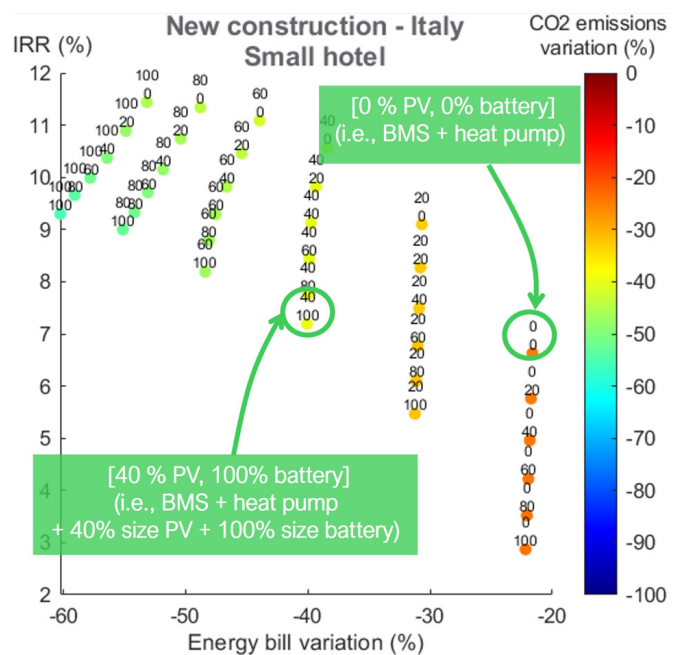
As previously detailed, the four low-carbon technologies examined within each use case undergo multi-stage modeling.

- The model's initial stage involves the installation of a Building Management System and replacing the existing heating and cooling system with a heat pump.

The state of the building after this first stage is represented by the dot [0% PV, 0% battery], which should be examined closely before moving to the remaining ones (see Box 1).

- Subsequently, the model simulates the installation of various microgrids consisting of PV systems and/or batteries. Every remaining dot of the scatter plot (e.g., [20% PV, 80% battery]) represents the situation of the building after 1) the installation of the BMS and the heat pump selected for the case and 2) the installation of a specific microgrid among the range of PV and battery sizes explored.

Exhibit 6. Example of the visualization tool conceived to optimize each use case's design (i.e., the sizing of the battery and the PV system). (the top number is the PV size, given as a percentage of the tested PV size in the use case, and the bottom number is the battery size, also as a percentage of the maximum tested battery size)



Such scatter plots are a powerful tool for decision-makers as, at one glance, they inform about all the potential sizing options and their contributions. It is important to highlight three important aspects of these scatter plot diagrams:

- In general, no microgrid sizing provides the best value for all the targeted KPIs. Decision makers should, therefore, make concessions when selecting a microgrid size.
- Not all sizing criteria can be represented in one scatter plot, both due to the finite dimensions of the plot (for readability, we have used only 3 dimensions: x-axis, y-axis, and color) and because some criteria are difficult to quantify or are intangible. The decision maker may add other criteria relevant to the investment decision (e.g., CAPEX and replacement cost requirements, increase in property value, brand image improvement, etc.).
- The displayed scatters correspond to a specific and finite sizing solution space (i.e., the range of tested PV and battery sizes). In this study, the solution space is defined according to the physical characteristics of each use case. If the shape of the scatter suggests that better solutions could be achieved by widening the solution space, this can still be done, provided that the new solutions are feasible.

⁹ For instance, the energy bill variation of dot [20% PV, 80% battery] is calculated as: (Energy bill [20% PV, 80% Battery]-Energy bill baseline)/(Energy bill baseline)×100, and similar calculations are done for the remaining dots, and for the CO2 emissions variation. Regarding the IRR calculation, it only includes the cashflows generated by the new elements installed, that are not already integrated in the baseline.

Box 1: Influence of [0% PV, 0% battery] dot for analyzing other PV and Battery sizing

The dot [0% PV, 0% battery] represents the state of the building after the installation of a BMS and a heat pump. The remaining dots represent the installation of various microgrid sizes, the BMS, and the heat pump. Consequently, the dot [0% PV, 0% battery] (i.e., the impact of the BMS and the heat pump) greatly influences how the remaining dots are colored or placed.

Color

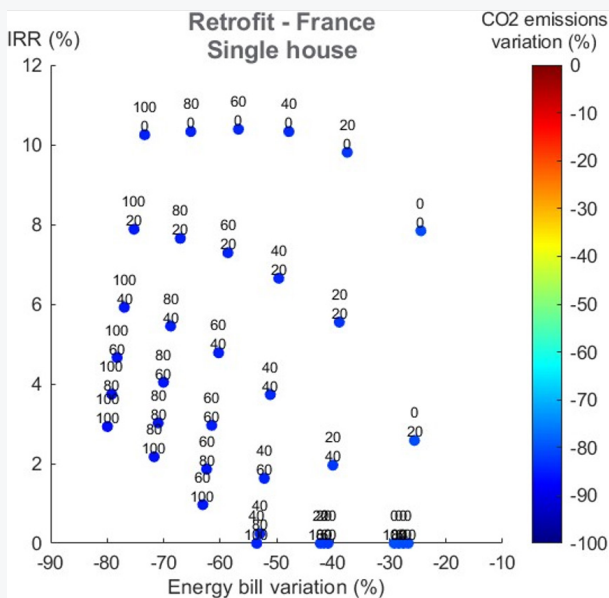
A clear example is observed in the retrofit single-house use case in France (see Exhibit 7).

In the baseline scenario, the gas-based heating system is responsible for most CO2 emissions. Consequently, replacing this system with a heat pump and implementing a Building Management System (BMS) already achieves an 80% reduction in CO2 emissions.

This significant reduction is partly due to France's low grid CO2 content, which results in only moderate additional emissions from the heat pump.

In comparison, increments in PV size do not lead to substantially greater reductions in CO2 emissions.

Exhibit 7. A scatter plot depicting the bill reduction, CO2 emissions reduction, and IRR obtained with all the tested PV and battery sizes in a France retrofit single house use case.

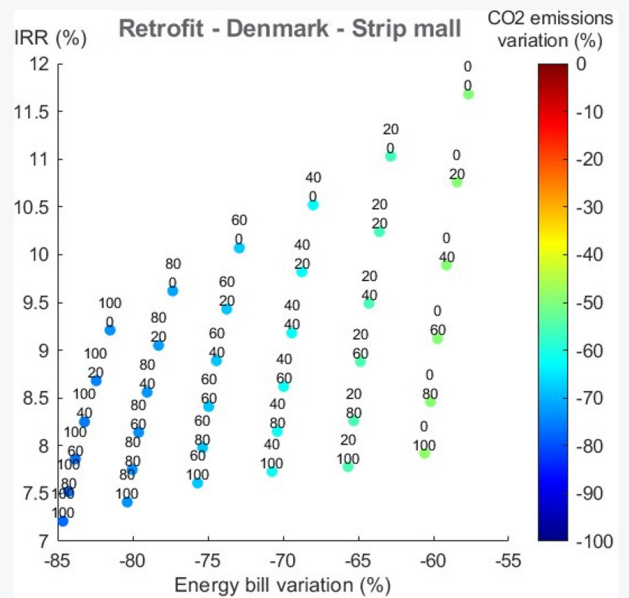


Positioning

It is important to note that simply increasing the PV or battery size is not enough to improve the Internal Rate of Return (IRR), even in the case when the additional bill reductions outweigh the extra CAPEX and replacement costs. In fact, the marginal IRR obtained from a size increment must exceed the IRR achieved with the previous size.

This reasoning also applies to scenarios with decreasing IRR. For instance, in Exhibit 8, the IRR of the [0% PV, 0% battery] configuration is 11.8%. A 20% PV size increment decreases this IRR to 11.0% because the marginal IRR provided by the additional PV is only 6.3% (lower than the initial 11.8%).

Exhibit 8. Scatter plot depicting the bill reduction, CO2 emissions reduction and IRR obtained with all the tested PV and battery sizes - Denmark retrofit strip mall use case.



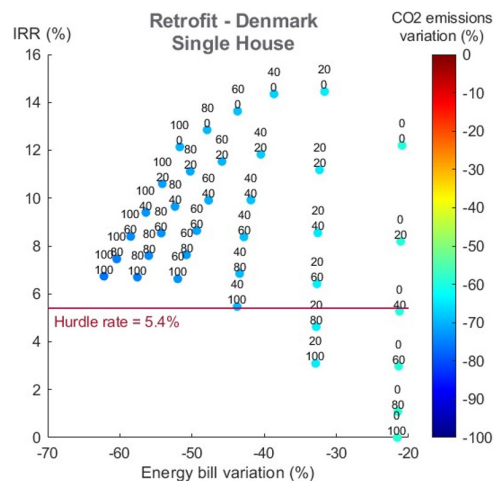
A method to assess the viability of projects in a multi-criteria strategy.

While we have developed a tool to visualize the space of sizing solutions, this alone is insufficient for assessing project viability. To accomplish this, we compare the Internal Rate of Return (IRR) of possible sizing options with the project's hurdle rate¹⁰ (also known as the minimum acceptable rate of return for the project).

Specifically, we display a horizontal line representing the selected hurdle rate on our visualization tool. This line delineates all viable sizing options above it, facilitating the profitability evaluation (see an example in Exhibit 9).

It's worth noting that alternative approaches using Net Present Cost (NPC) or Discounted Payback could also be employed, as detailed in Box 2.

Exhibit 9. Bill reduction, CO2 emissions reduction, and IRR were obtained for all tested PV and battery sizes in the Denmark single-house retrofit use case. The horizontal line depicts a hurdle rate to be compared with the IRR.



Box 2: Alternative Net Present Cost or Discounted Payback approaches

Instead of comparing IRR to a hurdle rate, the NPC or discounted payback could also be used for the profitability assessment. It is important to keep in mind that the equilibrium points of the three KPIs are aligned.

This is highlighted by Exhibits 10 and 11, where the same scatter plot in Exhibit 9 is represented, but the IRR is substituted by the NPC and by the discounted payback.

The dots with an IRR greater than the selected hurdle rate (i.e., the viable microgrid sizes), correspond to the dots with a negative NPC in Exhibit 10 and to the dots with a discounted payback smaller than the lifetime of the project in Exhibit 11.

Nevertheless, the growth monotony of these KPIs is not necessarily aligned, particularly when comparing IRR and NPC.

For instance, the dot with the highest IRR in Exhibit 9 is [20% PV, 0 % battery]. Exhibit 10 shows that the dot [40% PV, 0% battery] has a better NPC (more negative).

Indeed, the solution with a 40% size PV yields greater net earnings than the solution with a 20% size PV, which is why the former's NPC is better.

However, a 40% size PV also requires a greater investment than a 20% size PV. The earnings per dollar invested are better in the solution with a 20% size PV; the IRR is higher.

Exhibit 10. Scatter plot depicting the bill reduction, CO2 emissions reduction and net present cost obtained with all the tested PV and battery sizes, Denmark retrofit single house use case.

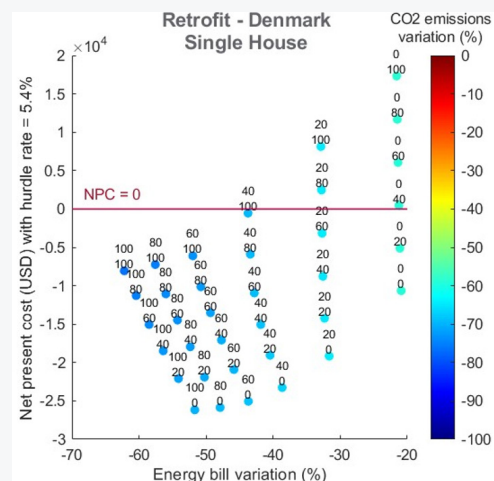
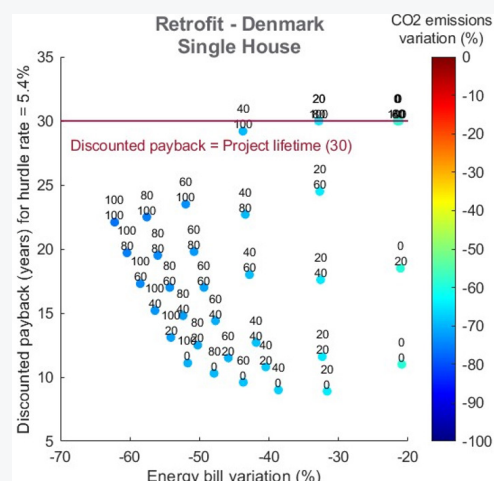


Exhibit 11. Scatter plot depicting the bill reduction, CO2 emissions reduction and discounted payback obtained with all the tested PV and battery sizes, Denmark retrofit single house use case.



¹⁰ Note that the hurdle rates and IRRs used in this study are expressed in real terms, unless stated otherwise. The technical meaning of a hurdle rate, as well as the difference between real and nominal rates is also explained in the Annex "Basic notions on profitability".

¹¹ Note that the discounted paybacks calculated by EMSF are upper bounded at the lifetime of the project. Therefore, the dots that lay right under the red horizontal correspond to non-viable microgrid sizes with discounted paybacks of 30 years or more.

Towards Net Zero Buildings - The Investment Case

Hurdle rate setting

Regardless of the KPI used, profitability is highly affected by the choice of discount rate. A discount rate is a tool used to determine the present value of future cash flows, reflecting the time value of money (i.e., accounting for the fact that a dollar today is worth more than a dollar in the future, as it can be immediately invested and yield interest).

For the private sector, companies set a discount rate equal to their minimum acceptable rate of return, also known as “hurdle rate”, and this hurdle rate is chosen as the weighted average cost of capital (WACC) of the company (LBNL, 2023; Damadoran, 2024). This is because the cost of capital reflects the return that the company obtains with its typical activity.

Therefore, in the context of green investments, for instance, setting the WACC as the hurdle rate implies no difference when assessing a decarbonization investment or any other investment under review by the company. Said differently, the company may weigh the decarbonization investment in competition with any other potential business investment (e.g., for a hotel owner, a competition between investing in a swimming pool or rooftop solar). Note, however that the choice of the hurdle rate value is very difficult and has been debated in economic literature for decades, but the most common hurdle rate is based on the weighted average cost of capital (Sami, 2014).

Additionally, companies shall factor in the uncertainties associated with a project or group of projects (e.g., decarbonization projects of a portfolio of buildings) (see Box 3).

As shown in Exhibit 12, WACC varies according to company types (BloombergNEF, 2024).

In practice, depending on the risk management approach of the company, this may be done in two ways¹²:

- Using a risk-adjusted hurdle rate, meaning adding a risk premium to the WACC for considering uncertainties (IEA, 2019). This can be done, for example, using the “risk-adjusted” method, which incorporates risks into the hurdle rate calculation, estimated from the historical returns of similar projects (FasterCapital, 2024).
- Using the company’s basic WACC, the risk is now factored into the project cash flows.

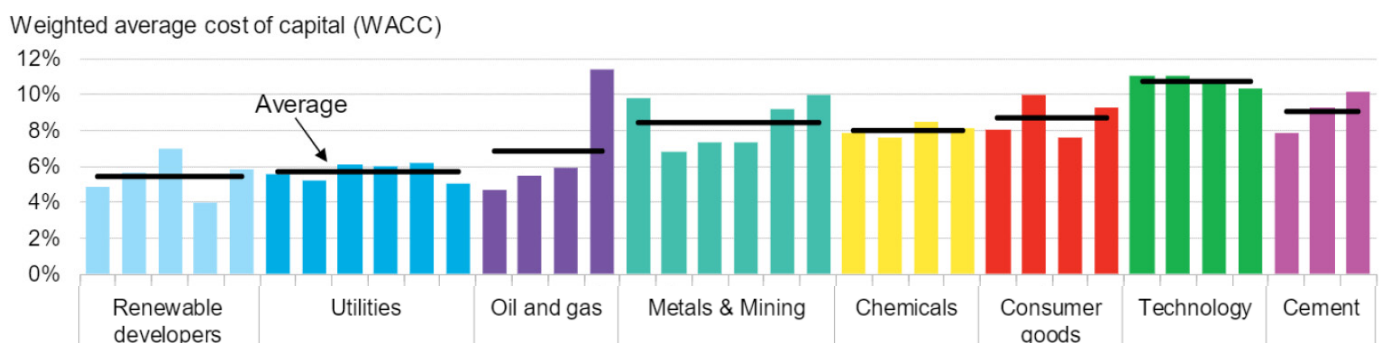
However, it should be noted that certain uncertainties may lead to positive impacts in terms of profitability, such as the potential green premiums resulting from decarbonization investments (see Box 3).

This same reasoning can be extended to investors different from private companies, such as public investors or households. Investments in buildings are primarily implemented by private stakeholders, firms, or individuals who incur upfront costs in the present and expect to recover the investment in the future thanks to energy bill savings (or carbon tax reduction).

For households, hurdle rates should be differentiated based on individual socioeconomic parameters rather than applied technology, as capital costs are more dependent on personal economic circumstances (BPIE, 2015). Loan rates can vary significantly between households, reflecting their unique socio-economic situations and lender-perceived risks.

Companies within the same sector typically face similar risks, such as market fluctuations, regulatory changes, and technological advancements. Therefore, their WACCs tend to reflect these common risks. In the next section, we use a sector-wide WACC to provide a standardized benchmark for comparing investment opportunities across different scenarios.

Exhibit 12. WACC for a selection of large companies, by Industry (BloombergNEF, 2024).



¹² One risk cannot be accounted in both cash flows and hurdle rate.

Box 3: Uncertainties, Green premium

Uncertainties

When considering investments, uncertainties can typically relate to market or project risks.

Market uncertainties can arise from several factors, such as sectoral cyclicality or specificities, unclear policies, or regulatory uncertainties.

- Sectoral sensitivity: Typically, hotels (with occupancy rates varying with seasonality) and retail (with rapid changes in consumer preferences) are more sensitive to economic crises than offices (stability of tenants, but with risk of vacancy) or hospitals, for example (inelastic demand for healthcare, stable cash flows from patient fees). Sectors with higher energy bills must consider the risk associated with energy price fluctuations.

- Government incentives volatility: Support that varies over time (tax breaks, rebates, grants, subsidies), such as the end of subsidies for heat pumps (FT, 2024), or risks of future penalties such as for non-compliance to energy efficiency or CO2 emission levels (NYC, 2024) can lead to risk premiums.

Project risks cover many risks such as building asset quality, project delays, value chain or project complexity, or technology deployed.

Older buildings with maintenance issues carry higher risks. Major metropolitan areas typically offer higher rental income and lower vacancy risks. Tenant creditworthiness also reduces the risk.

Technology-related risks are especially relevant for technologies at an early stage of market maturity, considering higher failure rates due to less experience (BPIE, 2015). However, decarbonization technologies considered in the scope of this research are all mature and vary merely for the considered building segments (only the single house case may differ a bit as being less complex when considering home controls and a heat pump).

Green premium

There is currently an extensive body of research concluding an increase in asset value (IEA, 2019; GBCA, 2008) and rental value (IEA, 2019; JLL, 2023; CBRE, 2021) from green investments. These historically targeted energy efficiency in buildings but now encompass more electrification of heating and microgrids (on-site solar and storage).

Green buildings often exhibit lower energy costs (lower energy consumption and on-site electricity from solar PV) and lower operational costs with the presence of energy management systems. They are also often more compliant with evolving environmental regulations, reducing exposure to holding stranded assets and mitigating potential future regulatory costs and liabilities. Green buildings, and in particular, those obtaining certifications like LEED or BREAM, can indeed increase property value (5-25% range) (IEA, 2019; GBCA, 2008), demonstrating environmental responsibility and commitment to sustainability. They also improve rent (5-30% range) (IEA, 2019; JLL, 2023; CBRE, 2021), increasing tenant attraction due to lower operating costs and a better sustainability image for the tenant.

Despite the growing recognition of the Green premium, skepticism remains regarding its consistent application in financial models. Some investors may still prioritize traditional metrics over sustainability considerations, potentially limiting the broader adoption of green building practices in investment strategies. Investors and financiers need to understand better the real risks and benefits of sustainable investments based on market evidence and performance history. Fundamentals such as the lower probability of default in the case of energy-saving loans or an increased value of assets due to higher energy performance need to be progressively recognized by banks and reflected in the pricing of their financing products (GBCA, 2008; JRC, 2018). So, a green premium is usually factored in the cashflows.

In the next section, we will select relevant hurdle rates for illustrative investment cases, but we will not add risk premiums or discounts for simplicity. Also, only the “financial” rates will be considered as we take the investor’s perspective. The concept of “social” rates exists (Copiello, 2021) but is not considered in this report.

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Choosing a set of hurdle rates for illustrative cases

As concluded in the previous section, selecting an appropriate hurdle rate is a complex task since this rate depends both on the type of investor and the investment project being evaluated.

In light of this, and to fulfill the main goal of the report (i.e., to discuss the sizing procedure of the low-carbon technology package), we chose several generic investor profiles and an approximate hurdle rate for each of them, which will feed Part III, presenting various case studies in which a use case (and its resulting scatter plot) is associated with one of these investor profiles (and its selected hurdle rate).

To obtain the approximate hurdle rates of the different investor profiles, we use a technical support document from the United States Department of Energy (U.S. Department of Energy, 2022). This document provides estimations of the hurdle rate usable by various investors (households, companies of different sectors, and public entities) when evaluating an investment in a high-efficiency appliance¹³. To do so, they assimilate the hurdle rate to the cost of capital (excluding any potential project premiums or discounts).

- For households, we derive the cost of capital from the Survey of Consumer Finances, which provides information about households' debt and investment products. The results are divided by income level since this notably affects the rates of the financial products available to households (see Exhibit 13).
- For companies, we estimate the average WACC of various sectors using the Damodaran Online database, which gathers and processes financial information of publicly traded companies (see Exhibit 14)
- Finally, we estimate the cost of capital of public entities (e.g., local or country-level governments) from US local bond rates and Treasury bond rates (see Exhibit 15).

Exhibit 13. Real cost of capital (in %) for US citizens per income categories, from (U.S. Department of Energy, 2022).

Type of Debt	Income Group						
	1	2	3	4	5	6	All
Mortgage	4.09	3.74	3.60	2.92	2.79	2.19	3.18
Home equity loan	4.29	4.34	3.86	3.24	3.11	2.45	3.35
Credit card	9.80	11.02	11.15	11.26	10.90	10.11	10.64
Other installment loan	6.14	7.09	5.98	5.33	4.54	4.42	6.10
Other line of credit	3.73	3.67	6.23	5.47	4.89	5.33	4.97
Other residential loan	6.53	6.41	5.22	4.96	4.33	3.99	5.32

Exhibit 14. Sectoral real WACCs (in %) in the US – for a set of large corporations, from (U.S. Department of Energy, 2022).

Sector	Observations	Total Firms	Mean WACC (%)
Education	23	801	7.12%
Food Sales	42	866	5.60%
Food Service	23	1840	6.34%
Health Care	54	5416	6.78%
Lodging	23	1619	6.35%
Mercantile	99	5510	6.88%
Office	449	45006	6.78%
Public Assembly	46	3698	7.17%
Service	156	15606	6.22%
All Commercial	929	80520	6.67%
Industrial	1,301	78249	7.16%
Agriculture	8	270	6.94%
Utilities	105	2132	4.14%
R.E.I.T/Property	53	4313	6.43%

Exhibit 15. Real cost of capital (in %) for US public entities, from (U.S. Department of Energy, 2022).

Sector	Observations	Mean Discount Rate (%)
State/Local Govt	30 years	3.21
Federal Govt	384 months	2.17

¹³ In particular, a high efficiency water heater.

¹⁴ Households: 1985-2019, Large corporations: 1998-2020, Public entities: 30 years

¹⁵ See the Annex "Basic notions on profitability", for more information regarding the nominal and real IRR.

¹⁶ It is worth to note that we did not address the Real Estate case (Rented office) because of the inability to get relevant data for the rents.

Note that, in all three cases, the hurdle rates are obtained from 20-year historical data (or more)¹⁴, so that the influence of major economic cycles is averaged. This is particularly appropriate for this report, in which the hurdle rate is used for illustrative purposes only and does not attempt to capture the most recent data. Additionally, the resulting rates are provided in real terms (and not nominal), which is again suitable since real IRRs are calculated in this report¹⁵.

Finally, it is essential to highlight that although the hurdle rates are obtained from US data, we use them for all geographies. This approach is viable because the resulting hurdle rates are only used for illustrative purposes. It allows for a single and coherent data source, which shows reliable and significant differences among households, companies, and public entities' hurdle rates (instead of having many scattered data sources that follow different calculation methods).

We chose the following five illustrative investment cases (investor profile x building segment x new construction or retrofit)¹⁶:

- A retail company owning its assets, which depicts the point of view of a typical private investor. This profile is used both in Case Study 1 and in Case Study 2 for a retrofit strip mall in Italy and a new construction strip mall in China, respectively. In both cases, it is supposed that the company would use its ordinary financing sources for the investment, and consequently, the "Large corporation" sectorial WACC from (U.S. Department of Energy, 2022) is used (6.9%).

- A hotel company is chosen in Case Study 3 for a new construction small hotel in Denmark. This profile also represents a private investor, but we assume in this case that the company has a net zero agenda that makes it favor CO2 reductions to the detriment of profitability. As mentioned above, it is supposed that the company would use its ordinary financing sources for the investment, and as a consequence, the "lodging" sectorial WACC of (U.S. Department of Energy, 2022) is used (6.4%).

- A public institution owning healthcare facilities is used in Case Study 4 for a retrofit hospital in Florida (USA South). The selected hurdle rate corresponds to the local government cost of capital calculated in (U.S. Department of Energy, 2022) (3.2%).

- A homeowner profile is used in Case Study 5 to address both the retrofit (5a) and new construction (5b) single-house use cases in France. This is done to emphasize that, if the household uses a single financial product for the investment, the hurdle rate may be subject to wide variations depending on the loan availability.

- o For the new construction of a single house, we suppose the household can include the low-carbon package investment in the mortgage loan. The provided mortgage rates (U.S. Department of Energy, 2022) go from 2.2% (high-income households) to 4.1% (low-income households).

- o For the retrofit of a single house, it is supposed that the homeowner will need to incur a less attractive consumer loan, such as an installment loan. The installment loan rates provided in (U.S. Department of Energy, 2022) go from 4.4% (high-income households) to 7.1% (low-income households).

Part III: Practicing optimization for a few investor profiles in selected segment

In the previous Part, we showed how to use the scatter plot tool when incorporating the hurdle rate of a given project. We now operationalize its usage for five selected illustrative case studies with Exhibit 16 providing a summary of the findings¹⁷.

Exhibit 16. Summary results for the five Case studies.

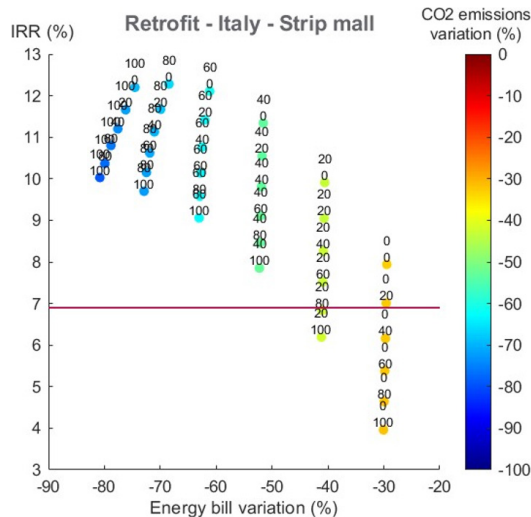
Case Study	PV Size Influence	Battery Size Influence	Project Viability	Key Takeaways
Italy Strip Mall Privately-owned Retrofit	Energy bill decreases with PV size increase, making IRR increase. But “diminishing returns” at higher PV sizes. CO2 emissions decrease with PV size increase.	CO2 emissions are not significantly affected by battery size increase. Energy bill reductions are moderate, leading to steep IRR decline with battery size increase.	Optimal sizing: [60-100% PV, 0% battery] for highest IRR. Concessions on profitability can allow for small battery inclusion.	Demonstrates the trade-off between profitability and other factors.
China Strip Mall Privately-owned New Construction	The energy bill reductions obtained as the PV size increases over 40% are very limited (“diminishing returns” issue), making the IRR decrease.	Battery size increase provides more significant bill reductions, leading to a less pronounced IRR decline (or even to a stable IRR) Such bill reductions are partly due to a high electricity price spread, considerable excess PV production and nonattractive sellback price.	Potential for 40-60% PV and 100% battery size with acceptable IRR.	Highlights the importance of considering tariff structures (price spread, sellback options) in battery evaluation.
Denmark Small Hotel Privately-owned New Construction "Net Zero" Agenda	Inclusion of smaller or larger PV system decreases IRR, due to low marginal returns compared to heat pump/BMS alone.	General trends like Case study 1.	Prioritizes CO2 reduction over maximum IRR. A 100% PV with 0% battery considered acceptable despite a slight IRR reduction compared to heat pump/BMS alone.	Emphasizes the importance of investor priorities (e.g., environmental goals) beyond pure profitability.
USA South Hospital Publicly-owned Retrofit	General trends like Case Study 1, but with very minor energy bill reductions, IRR increases and CO2 reductions. Because the maximum PV size of the retrofit hospital segment (i.e., available roof space) is small if compared to the electrical consumption.	Initial battery size increments lead to significant bill reductions due to demand charge reduction.	Maximum IRR (100% PV and 20% battery) is modest, but viable since public investors have low hurdle rates. Such investors may also prioritize factors like resilience and social welfare, potentially accepting lower IRRs.	Highlights the importance of considering specific tariff components (e.g., demand charges) in battery evaluation. Also emphasizes the need to adapt the hurdle rate to the investor profile.
France Single House Privately-owned Retrofit & New Construction	Limited CO2 reduction from PV due to low grid CO2 content. New Construction only: Greater bill and IRR variations with PV size increase, due to larger potential from PV production (i.e., larger available roof space).	General trends like Case Study 1, with particularly steep IRR declines (partially due to greater battery CAPEX in residential segments).	Hurdle rates vary significantly based on the homeowner's financial situation and investment type (mortgage vs. consumer loan).	Emphasizes the importance of considering specific market factors (e.g., grid CO2 content, available roof space) in microgrid design. It also highlights the dependence of a household's hurdle rate on its socio-economic situation.

¹⁷ For a vision of the results for the 126 use cases (scatter plots to which hurdle rates should be applied), see the Annex.
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Case study 1: Retrofit of a privately owned mall, in Italy

The first case study of this series describes the case of the retrofit of an owner-occupied (strip) mall in Italy. Exhibit 17 displays the scatter plot associated with it, with the horizontal line corresponding to the hurdle rate of the owner investor.

Exhibit 17. Bill reduction, CO2 emissions reduction and IRR obtained for all tested PV and battery sizes, Italy strip mall retrofit use case. The horizontal line depicts the investor's hurdle rate, to be compared with the IRR.



Trends

The scatter plot in Exhibit 17 is quite representative of the most common IRR, bill, and CO2 variation trends as the microgrid size changes¹⁸.

Regarding the influence of the PV size:

- The CO2 emissions decrease as the PV size increases, as grid imports are substituted with PV production (see change in color, from yellow to blue).

- o The amount of CO2 emissions reduction achieved when PV size increases is notably influenced by segment-dependent characteristics. Specifically, it is influenced by the ratio between the maximum PV size (determined by the segment's available roof space) and the building's electrical consumption (after heat pump and BMS deployment).

- The energy bill also decreases as the PV size increases because the "free" PV production is used to feed the electrical load (avoiding imports of energy from the grid) and, at some point in time, to sell the excess on-site production to the grid. Such bill reductions, discounted to the present, often outweigh the additional CAPEX from PV size increments and even lead to IRR improvements.

- o Regarding CO2 emissions, the bill reduction achieved with a PV size increase is notably influenced by the ratio between the maximum PV size and the building's electrical load.

- o It is also common to see a less efficient reduction of the energy bill reduction per unit of size increase for large PV sizes (i.e., the bill reductions achieved when going from 0% PV to 20% PV are higher than when going from 80% PV to 100% PV). In consequence, the IRR may decrease in some cases.

This is due to diminishing returns. For the first 20% of PV installed, a substantial portion of the PV production can be directly used to feed the electrical load. However, as the PV size increases, there are more times in the year when the PV production exceeds the load consumption, so it is exported to the grid (unless the battery can recover it). Even if the electrical tariff allows for sellback, this exported production may not deliver as great returns as the PV production used to substitute the grid imports since the average energy sellback price is often smaller than the average purchase price.

Regarding the influence of the battery size, there is less of a general trend than for the PV size, since the battery behavior is highly dependent on the tariff structure of each use case (see Box 4). However, some aspects observed in Exhibit 17 are seen in many other use cases:

- CO2 emissions are not notably affected by battery size changes compared to the CO2 emissions reduction generated by the PV size increments.

- o If no PV is installed, CO2 emissions do not change with the battery size increments (only negligible changes due to the battery's energy losses). For big PV sizes, if there is excessive PV production not directly consumed by the load, the battery can recover it and use it to feed the load later. This avoids importing energy from the grid, leading to moderate CO2 emissions reductions.

- The bill reductions generated by the battery increments are moderate compared to the required CAPEX and replacement costs, leading to a decline in the IRR.

- o In the particular use case of Exhibit 17, we observe two battery behaviors with respect to bill reduction¹⁹.

- o On one hand, when there is no excessive PV production (i.e., low PV sizes), the battery is used to store grid energy when purchase prices are low to feed the load later when prices are high. However, the bill reductions achieved with this behavior are negligible since the purchase prices are very flat in Italy (i.e., a small gap between high and low prices), resulting in IRR reduction.

- o On the other hand, for big PV sizes, the battery can also recover the excessive PV production and use it to feed the load later, as previously explained. As a result, the bill reductions achieved with the battery increments are larger, and the IRR decline is less pronounced.

- o However, even if the battery increments lead to insufficient bill reductions in many use cases, there are some notable exceptions to this trend. More precisely, we have observed some situations where the battery provides considerable bill reductions, which prevent the IRR from declining and can even increase it. These situations are presented in Case Study 2 and Case Study 4.

- o It is important to note that these situations do not apply to residential use cases where the increase in the battery size always produces a drop in the IRR. A factor contributing to this is that the CAPEX of residential battery systems, in USD per kWh installed, is much bigger than the CAPEX of commercial battery systems (Minier, 2024).

¹⁸ The scatter plots of all the 126 studied use cases are gathered in the Annex (see Scatter plots of 126 use cases), where the diversity of IRR, bill, and CO2 evolution trends can be appreciated.

¹⁹ In this use case the electricity tariff includes a fixed component and an energy component, and that it allows for the sellback of energy.

Project viability

As shown in Exhibit 17, the owner investor can choose among the 30 viable designs given the hurdle rate (i.e., dots above the horizontal line). To make this selection, the investor should weigh up the three decision criteria displayed in the scatter plot and other key criteria not reflected in the plot (e.g., initial CAPEX limit, improved brand image, etc.). As no microgrid design can optimize all criteria, concessions should be made.

If profitability is the main or only driver, then:

- No battery should be installed, as it drives down the IRR in this use case.
- The [60% PV, 0% battery], [80% PV, 0% battery], and [100% PV, 0% battery] designs provide similar IRRs. However, it is important to note that their CAPEX requirements are different and that the investor may not have the capacity to pay out such amounts at the beginning of the project (thus the necessity of analyzing the spread of the cashflows throughout the lifetime of the project, in addition to the profitability).

If the investor can make concessions regarding profitability, then it is possible to install a “20% or 40%” battery sizing, as it results in a reasonable decrease in profitability but can bring other value (increased property value, security against electricity tariff changes, etc.).

Another interesting fact to highlight in this Case study is that the microgrid sizing corresponding to the lowest energy bill (i.e., [100% PV, 100% BAT]) is far from being the best in profitability. This underscores the importance of multi-factor assessment for microgrid sizing (in opposition to single-variable optimization strategies, which only provide partial information about the sizing solution space).

Box 4 : Battery Behavior

In our modeling, the dispatch optimization is achieved through a model predictive control algorithm calculating the setpoints of the battery (control action) using forecasts of the energy costs, the uncontrollable building loads, and of the PV production.

The objective function of the algorithm aims at 1) minimizing the energy and power²⁰ components of the electrical bill, and 2) making the power imported and exported from the grid respect a certain limit (However, this second objective was not activated for the simulations presented in this Part²¹)

Therefore, it is difficult to accurately explain the behavior of the battery at any given time since it is governed by an optimization problem that considers many current and future data. However, it is possible to explain, in a simplified manner, the main battery actions:

- The battery is preferably charged with PV energy since the optimization problem sees PV production as a free source that does not increase the electrical bill. If this is impossible, it is charged with energy imported from the grid (giving preference to hours with low energy prices).
- Regarding the discharge of the battery, it is used for three purposes:
 1. To reduce grid import peaks if the tariff includes a power component or if the grid power limit option is activated in the battery control.
 2. Avoid feeding the load with grid imports when energy prices are high.
 3. If the tariff allows for sellback, to export energy to the grid.

Note that these three potential discharging actions are only activated if the gains obtained with them are higher than the costs required to charge the battery and the costs associated with the losses in the charging/discharging process. This can be particularly challenging for action 3. If the battery is charged with grid energy, the sellback price should exceed the purchase price. If it is charged with PV energy, storing it and exporting it later should be more worthwhile than exporting it directly as it is produced (otherwise, part of the energy is lost in the charging/discharging process).

It's also crucial to note that the priority that the dispatch optimization assigns to each of the discharging actions depends on the relative weights of the electrical bill components.

²⁰ The energy component corresponds to the cost of the energy volumes imported from the grid, minus the sales for the energy exported to the grid (if sellback is authorized). The power component may take two forms:

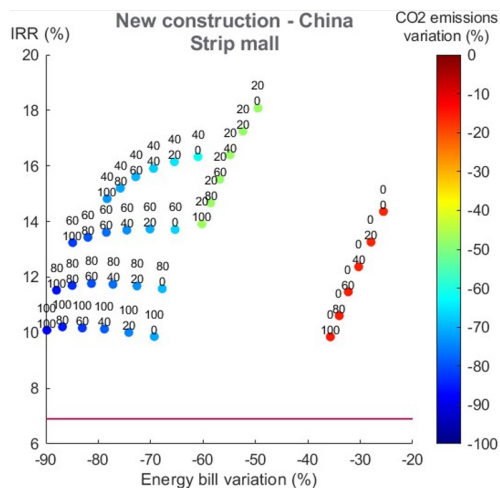
- Demand charges: the power cost is based on the effective peak power reached within a period.
- Subscribed power: the customer subscribes to a certain power level and penalties may apply if such level is exceeded.

²¹ However, to study the grid burden issue, the simulations of the retrofit use cases were repeated, with the grid limit option activated. These simulations are detailed in the Grid Annex.

Case study 2: New construction of a privately-owned mall, China

This case study takes the same private investor profile as Case study 1, but this time for a new construction strip mall in China.

Exhibit 18. Scatter plot depicting the bill reduction, CO2 emissions reduction and IRR obtained with all the tested PV and battery sizes, China new construction strip mall use case. The horizontal line depicts the investor's hurdle rate, to be compared with the IRR.



This use case is highlighted because Exhibit 18 depicts one situation where the battery can lead to considerable bill reductions while not heavily deteriorating the IRR. In broad terms, the battery presents the two same behaviors as in Case study 1, but it leads to greater bill reductions in this case²².

When there is no excessive PV production (i.e., low PV sizes), the battery stores grid energy when purchase prices are low to feed the load later when prices are high. The high purchase price spread in the China commercial electricity tariff partly explains the greater bill reductions achieved.

For big PV sizes, the battery can recover the excessive PV production and feed the load when grid purchase prices are high. The greater bill reductions achieved with respect to Case Study 1 are partly explained by the considerable excess PV production (new construction strip mall is one of the segments with the highest ratio between the maximum PV size and the electrical load of the building). Additionally, the grid sellback price is nonexistent or small compared to the purchase price (otherwise, it may be more advantageous to sell the excess PV production to the grid). These features are particularly noticeable in various commercial new construction use cases in Spain and China.

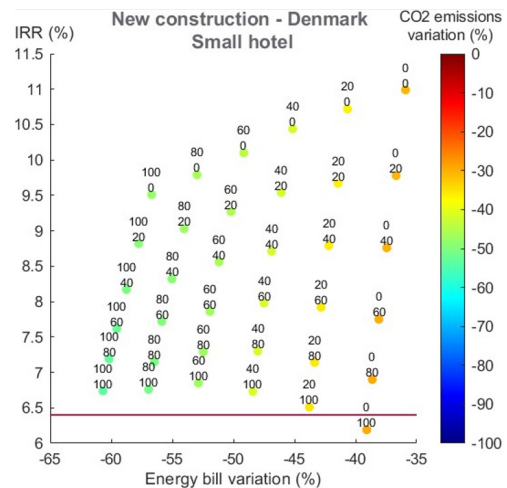
The above trends make the battery more appealing for the micro-grid sizing process. If the investor is willing to make certain profitability concessions, installing a 40 % or 60% PV and a battery in the highest size range is plausible while having a good margin between the IRR and the investor hurdle rate. As explained in the previous case studies, these concessions should bring other benefits, and the investor should also be able to bear the CAPEX and replacement costs required by the battery.

Regarding the influence of the PV system, it should be noted that the “diminishing returns” issue mentioned in Case Study 1 is even stronger in this second case study. Indeed, when the PV size increases over 40%, the additional bill reductions obtained are very limited, decreasing the IRR.

Case study 3: New construction of a “Net zero agenda” privately-owned small hotel in Denmark

In this Case study, the investor represents a privately owned hotel company having a net zero agenda. However, Exhibit 19 shows a PV behavior that differs from the general trend in Case Study 1: including a PV system, even in the smallest range, drives down the IRR.

Exhibit 19. Scatter plot depicting the bill reduction, CO2 emissions reduction, and IRR obtained with all the tested PV and battery sizes, Denmark's new construction small hotel use case. The horizontal line depicts the investor's hurdle rate, which can be compared with the IRR.



As explained in Box 1, this is because the marginal IRR provided by the PV system is lower than the IRR obtained with the heat pump and the BMS only (i.e., with [0% PV, 0% battery]). This behavior is seen in 9 out of the 126 studied use cases.

Despite this, the ambition of an investor with a net zero agenda should lead him tolerate a reduction in profitability²³ in exchange of a reduction in CO2 emissions. Indeed, the heat pump and BMS of this case study provide a CO2 reduction of 31%, which can reach 48% if a PV system sized at 100% is added. Moreover, the IRR of the solution [100% PV, 0% battery] is more than 3 points above the investor's hurdle rate.

²² In this use case, the electricity tariff includes an energy component but does not allow for the sellback of energy.

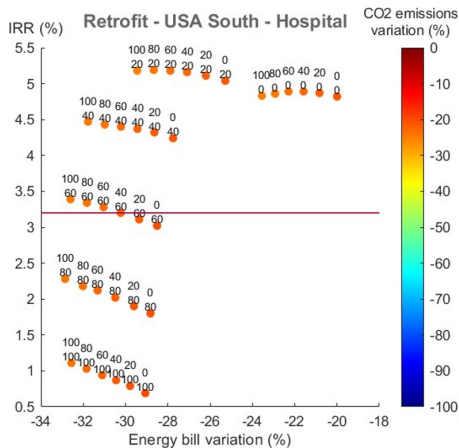
²³ And eventually accept to go even lower than the hurdle rate.

Towards Net Zero Buildings - The Investment Case

Case study 4: Retrofit of a publicly owned hospital, USA South

This case study, in contrast to the previous ones, uses a public investor profile (e.g., a local government) owning a healthcare facility. The hurdle rates of public investors can be significantly lower than those of private investors, allowing them to contemplate projects with moderate returns, such as in Exhibit 20.

Exhibit 20. Scattered plot depicting bill reduction, CO2 emissions reduction and IRR obtained for all tested PV and battery sizes, USA South retrofit hospital. The horizontal line depicts the investor's hurdle rate, to be compared with the IRR.



Public investors may also have some criteria that differ from those of private investors, such as those related to social welfare (e.g., job creation linked to the promotion of microgrid technologies). Additionally, hospitals are critical infrastructures where continuity of supply is key, and this may encourage the installation of bigger batteries for resilience purposes to the detriment of profitability. In this case study, a 40% battery reduces one point from the maximum IRR but leaves a margin of more than one point above the investor's hurdle rate.

Looking at Exhibit 20 highlights another situation where the battery trends are singular²⁴. We see here that the first battery size increments (top left) lead to considerable bill reductions (compared to the bill reductions achieved with the PV size increments). This behavior is observed in the commercial use cases in USA South, Canada, and USA West. In some, the first battery increments even lead to notable IRR increments. The main factor driving this situation is that a small battery allows the removal of the grid import peaks to reduce the demand charges, which are an essential part of the electricity bill in such cases²⁵.

On another note, the trends observed as the PV size increases are similar to those of Case Study 1, but with very minor energy bill reductions, IRR increments, or CO2 reductions. This is due to the low potential for PV production, as the retrofitted hospital is one of the studied segments with the lowest ratios between the maximum PV size (determined by the available roof space) and the electrical consumption of the building.

Case Study 5: Retrofit and new construction of a privately-owned single house in France

This final case study addresses the specificities of the homeowner investor profile.

- First, it emphasizes the potential variations of the hurdle rate rooted in the differences between the financial products available for each kind of investment.

For new construction, we can suppose the investment will be included in the mortgage loan required to finance the house. On the contrary, we can assume that the homeowner will need to take out a consumer loan with higher interest rates for a retrofit.

- Second, this case study shows that the hurdle rate of households also varies with their socio-economic situation²⁶, since high-income households have access to more attractive interest rates and, therefore, to lower hurdle rates.

Exhibit 21. Scatter plot depicting bill reduction, CO2 emissions reduction, and IRR obtained for tested PV and battery sizes and France single-house retrofit use cases. The horizontal lines depict the investor's hurdle rate, which is to be compared with the IRR.

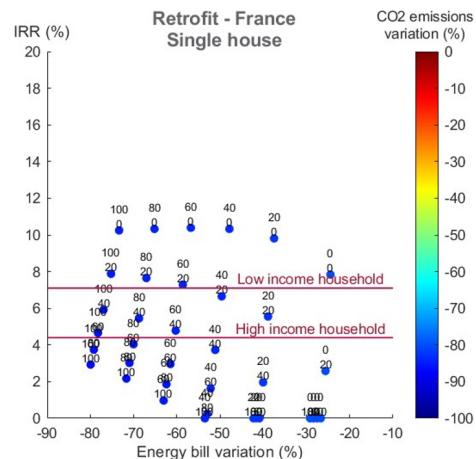
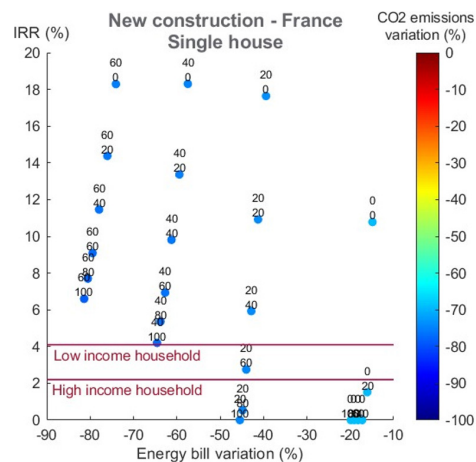


Exhibit 22. Scatter plot depicting bill reduction, CO2 emissions reduction, and IRR obtained for tested PV and battery sizes and France single-house new construction use cases. The horizontal lines depict the investor's hurdle rate, which is to be compared with the IRR.



- Both in the retrofit and the new construction case:
 - o The electrification of the heating system leads to robust CO2 reductions (see the dot [0% PV, 0% BAT] in Exhibits 21 and 22). This is because France has a low grid CO2 content. Consequently, the PV size increments do not provide significant additional CO2 reductions. Similar behaviors occur for the Canadian and Danish geographies.
 - o The increase of the battery size, although leading to noticeable bill reductions, causes a steep decrease in the IRR. One of the factors contributing to this is the high CAPEX considered for residential battery systems.
- The new construction case²⁷
 - o benefits from more significant bill and IRR variations as the PV size changes. This is a common trend, explained by the fact that larger maximum PV sizes are considered for new construction buildings (because of greater available roof spaces).

²⁴ In this use case, the electricity tariff includes a fixed component, an energy component (with sellback authorized) and a power component (in the form of demand charges).
²⁵ Note that the commercial electricity tariff of USA Northeast also includes demand charges, but the described behavior is barely noticeable because the demand charges are small in comparison to the other components of the electricity tariff.
²⁶ Similarly, small businesses usually exhibit a higher cost of capital than large corporations.
²⁷ NB: some microgrid sizing are not displayed in Exhibit 22 as these sizing got excluded because they make the building becoming net producer sites (i.e., PV farm-like) on a yearly basis i.e., annual sales of energy exported to the grid exceed the annual costs of imported energy.

Part IV: Example of a multi-criteria sizing rule

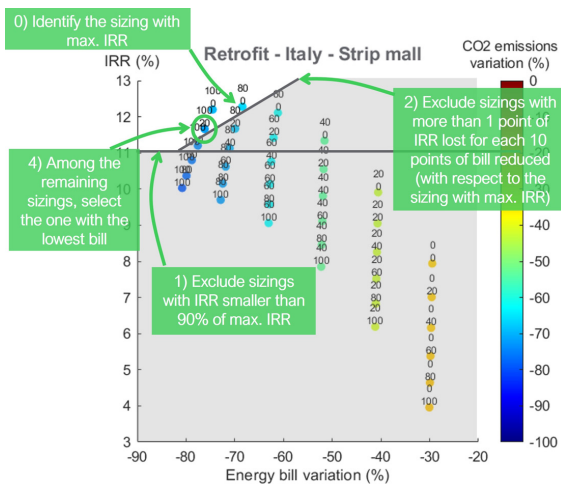
As a final highlight, we propose a simple microgrid sizing rule combining two criteria (bill reduction and IRR) that we have applied to all the 126 use cases addressed in this report. Of course, this rule is not meant to be a model to be followed (as said before, a microgrid sizing procedure must be designed according to the specificities of each investor and may consider many other criteria).

This exercise aims to provide a generic view of the results obtained by mixing two criteria and the improvements achieved concerning our previous report (in which a minimum bill sizing rule was used)²⁸.

The selected sizing rule consists of four steps, described hereafter and in Exhibit 23²⁹.

1. Identify the (PV, Battery) sizing with the maximum IRR,
2. Exclude sizing below 90% of the maximum IRR,
3. Exclude sizing for which a one-point IRR decrease provides less than 10% points of bill reduction (otherwise said, allow IRR degradation only if it brings value through bill reduction),
4. Select the one providing the maximum bill reduction among the remaining options.

Exhibit 23. Illustration of the application of the designed sizing rule.



The heatmaps gathered in Exhibit 24 display the battery sizes, PV sizes, bill reductions, CO2 emissions reductions, and IRRs resulting from applying the sizing rule.

PV and battery sizing

The general trend for PV systems is to select a size of 100% (about 70% of the cases). This denotes that increasing the PV size contributes to an increased or stable IRR and a bill reduction. However, there are segments for which smaller PV sizes are selected (single house retrofit and new construction, secondary school new construction, or strip mall new construction):

- In some cases, this is explained by the already-mentioned diminishing returns issue (i.e., as the PV size increases, the bill reductions achieved are more moderate, making the IRR stagnate or even decrease).

- In other cases, the simulations with the largest PV sizes have been excluded from the sizing solution space (as the annual energy sales exported to the grid exceed the annual costs of imported energy).
- There are five cases with no PV, four of which are located in Denmark. This is because the IRR achieved with the heat pump and BMS package is higher than the marginal IRR provided by the PV size increments, leading to a marked decline in the IRR as the PV size increases.

Batteries are not selected in about 60% of the use cases since they deliver insufficient bill reductions and lead to steep declines in the IRR. Note that these 60% include all the residential use cases. One of the underlying causes is that the CAPEX per kWh installed for residential battery systems is much higher than the CAPEX for commercial battery systems.

Nevertheless, in the remaining 40% of use cases, a battery is attractive regarding bill reduction and IRR, which are concentrated on the commercial segments of specific geographies. In China:

- The battery provides a noticeable part of the bill reduction by charging energy from the grid when purchase prices are low and to feed the load when purchase prices are high (note that there is a high spread of the purchase price in the commercial electricity tariff of China).
- In some use cases with a considerable excess PV production, the battery also recovers PV production, it is used to feed the load, with no sellback.

These same two battery behaviors are observed, to a greater or lesser extent, in the Spain use cases when battery deployment is present. In some of these use cases, batteries also contribute to reducing the power component of electricity bills, which in Spain is based on subscribed power capacity. Furthermore, in USA West, USA South, and Canada, batteries enhance their economic viability by mitigating demand charges, thus optimizing the power-related elements of electricity bills.

Output KPIs

Regarding CO2 emissions and energy bills, there are good reduction levels for retrofitting and constructing new structures. The mean CO2 emissions reduction is 50% for retrofit and 45% for new construction, while the mean bill reduction is 46% for retrofit and 50% for new construction.

Both KPIs are more modest in the hospital and large office segments (for both retrofit and new construction), as well as in the small hotel retrofit segment. These are precisely the segments with the lowest ratios between the maximum PV size (determined by the segment's available roof space) and the building's electricity consumption (after the introduction of the BMS and the heat pump). Therefore, increasing the PV size in such a segment does not lead to remarkable improvements in billing or CO2.

²⁸ Another example of two criteria could have been IRR and CO2 reduction.

²⁹ Note that this sizing rule does not take into consideration a hurdle rate. However, if the reader has a preferred hurdle rate for any of the use cases addressed, such rate can always be compared to the IRR obtained with the designed sizing rule. For instance, in Exhibit 25, the resulting IRR are compared to the hurdle rates derived in Part II (although these correspond to the US, they are applied for all geographies for the sake of simplicity).

Towards Net Zero Buildings - The Investment Case

Regarding profitability, almost all cases exhibit a positive investment case, i.e., complying with profitability targets while halving the energy bill and CO2 emissions, which is a major finding.

The mean IRR is 7.7% for retrofit use cases and 12.6% for new construction³⁰.

We observe two outlier cases with a remarkably high IRR:

- The new construction strip mall in Spain (large roof)
- Denmark cases more generally (key role of the heat pump).

Conversely, we observe small IRRs:

- For both retrofit and new construction in USA South region (low heating need while we install a heat pump)
- Retrofit in Canada and USA Northeast regions (low gas price making the heat pump investment case difficult)
- Globally the Large Office segment (small roof).

Exhibit 24. Results obtained with the designed sizing rule ("mixed IRR – bill"), for the 126 use cases under study.

		SIZING RULE "MIXED IRR - BILL"																	
		RETROFIT					NEW CONSTRUCTION												
PV SIZE (% of max. tested size per use case)		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S
Private investor	Large office	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Small hotel	100	100	100	100	100	100	100	100	100	100	100	60	100	100	100	100	100	100
	Strip mall	100	100	0	100	100	100	100	100	100	60	20	0	40	40	20	0	40	20
Househ.	Mid. apart.	100	100	100	100	100	100	100	100	100	100	100	100	100	100	80	100	100	100
	Single house	100	100	60	100	40	40	100	40	40	60	100	20	60	40	20	60	20	20
Public investor	Hospital	100	100	0	100	100	100	100	100	100	100	100	0	100	100	100	100	100	100
	Sec. school	100	100	100	100	100	100	100	100	100	60	80	80	80	80	80	60	40	40

		SIZING RULE "MIXED IRR - BILL"																	
		RETROFIT					NEW CONSTRUCTION												
BATTERY SIZE (% of max. tested size per use case)		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S
Private investor	Large office	100	40	0	0	0	20	0	100	100	20	40	0	0	0	0	0	40	20
	Small hotel	20	0	0	0	0	0	0	80	40	40	100	0	0	0	100	0	80	60
	Strip mall	60	100	0	20	20	100	0	100	40	60	0	0	0	20	0	0	100	40
Househ.	Mid. apart.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Single house	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Public investor	Hospital	20	0	0	0	0	0	0	20	20	40	0	0	0	0	0	0	20	20
	Sec. school	100	100	0	40	0	40	0	100	40	100	100	0	20	0	100	20	100	60

		SIZING RULE "MIXED IRR - BILL"																	
		RETROFIT					NEW CONSTRUCTION												
CO2 EMISSIONS VARIATION (% relative to baseline)		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S
Private investor	Large office	-47	-19	-34	-53	-25	-25	-23	-16	-17	-20	-14	-17	-24	-17	-16	-15	-15	-16
	Small hotel	-48	-29	-40	-56	-35	-35	-32	-30	-31	-53	-53	-44	-55	-46	-55	-43	-49	-51
	Strip mall	-81	-72	-50	-88	-72	-77	-65	-71	-68	-83	-47	-41	-84	-73	-55	-25	-69	-56
Househ.	Mid. apart.	-73	-37	-65	-87	-57	-56	-47	-51	-49	-52	-41	-46	-55	-44	-40	-41	-44	-43
	Single house	-77	-44	-68	-84	-60	-59	-54	-53	-50	-69	-43	-58	-75	-52	-48	-48	-42	-40
Public investor	Hospital	-43	-19	-33	-61	-31	-29	-23	-25	-25	-40	-18	-16	-39	-23	-22	-19	-23	-22
	Sec. school	-73	-49	-63	-81	-57	-58	-51	-57	-56	-67	-77	-63	-65	-64	-76	-58	-60	-60

		SIZING RULE "MIXED IRR - BILL"																	
		RETROFIT					NEW CONSTRUCTION												
ENERGY BILL VARIATION (% relative to baseline)		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S
Private investor	Large office	-16	-30	-40	-24	-23	-30	-22	-31	-32	-14	-22	-18	-17	-17	-18	-15	-26	-25
	Small hotel	-24	-34	-44	-31	-34	-31	-30	-42	-38	-55	-61	-49	-49	-53	-54	-55	-65	-68
	Strip mall	-60	-81	-58	-71	-76	-74	-69	-80	-79	-82	-50	-49	-67	-79	-47	-19	-80	-55
Househ.	Mid. apart.	-34	-52	-38	-48	-50	-43	-37	-64	-61	-60	-52	-43	-55	-50	-39	-58	-81	-67
	Single house	-64	-72	-44	-73	-50	-44	-76	-64	-56	-74	-90	-32	-74	-52	-35	-83	-54	-43
Public investor	Hospital	-10	-29	-40	-28	-27	-32	-22	-23	-29	-13	-22	-21	-22	-22	-25	-18	-27	-30
	Sec. school	-15	-65	-70	-57	-57	-54	-47	-61	-63	-74	-79	-90	-88	-87	-75	-80	-73	-71

		SIZING RULE "MIXED IRR - BILL"																	
		RETROFIT					NEW CONSTRUCTION												
INTERNAL RATE OF RETURN (%)		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S
Private investor	Large office	0,9	1,6	5,3	3,0	4,2	4,0	2,1	9,1	0,0	10,8	3,7	3,4	6,0	8,5	6,9	4,3	13,4	2,8
	Small hotel	9,6	6,8	8,9	8,0	9,9	14,3	5,9	13,2	2,1	14,0	7,9	10,1	9,1	11,4	14,3	7,7	12,0	3,1
	Strip mall	9,4	8,6	11,7	8,6	11,7	15,9	6,5	14,2	3,7	15,8	18,1	34,9	14,5	17,4	31,7	14,7	19,0	4,6
Househ.	Mid. apart.	1,2	10,9	12,4	10,1	10,7	10,9	5,3	9,2	0,5	13,4	18,4	24,0	18,6	16,9	20,1	20,1	23,3	4,9
	Single house	3,5	11,6	13,6	10,3	11,9	11,1	8,1	9,1	0,4	10,5	18,3	22,1	18,3	17,1	19,7	17,9	15,1	3,2
Public investor	Hospital	4,1	9,4	15,7	11,2	14,4	13,4	7,6	14,7	5,2	7,9	9,8	13,3	10,8	13,2	13,9	7,2	15,4	5,0
	Sec. school	0,0	9,1	7,0	4,5	6,8	5,9	2,6	9,0	1,7	11,7	6,3	5,9	7,8	11,6	7,6	7,2	14,7	3,3

*HR: hurdle rate. US Hurdle rates used for all geographies: 6,7% for private investors (retrofit and new construction), 5,8% for households (retrofit), 3,2% for households (new construction) and 3,2% for public investors (retrofit and new construction)

³⁰With the caveat that the IRR calculated by EMSF, and used in this report, is lower bounded at 0%.

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Comparison of the multi-criteria proposed rule with the bill optimization rule of our previous research

In this section, we offer to compare the results obtained in this report (trade-off “optimizing” the energy bill and the payback at the same time) with the results from our previous research (only optimizing the bill).

Comparison is exhibited in Exhibit 25, which displays the energy bill reduction and the simple payback obtained with both methods³¹.

Going from “minimum bill” to “mixed IRR – bill” allows for a considerable improvement of the profitability (average reduction of the simple payback of 5 years, both for retrofit and new construction) in exchange for a moderate degradation of the bill reduction (average increase of the bill in 5 points for retrofit and 10 points for new construction).

This result underscores the importance of multi-factor analysis for microgrid sizing (in opposition to single-variable optimization strategies, which only provide partial information about the sizing solution space).

Exhibit 25. Results obtained in our previous report (rule “minimum bill”) and with the newly designed sizing rule (“mixed IRR – bill”) for the 126 use cases under study.

SIZING RULE "MIXED IRR - BILL"																			
RETROFIT										NEW CONSTRUCTION									
ENERGY BILL VARIATION (% , relative to baseline)																			
										Legend									
										< -20	>= -20 & < 0	> =0							
	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	
Private investor	Large office	-16	-30	-40	-24	-23	-30	-22	-31	-32	-14	-22	-18	-17	-17	-18	-15	-26	-25
	Small hotel	-24	-34	-44	-31	-34	-31	-30	-42	-38	-55	-61	-49	-49	-53	-54	-55	-65	-68
	Strip mall	-60	-81	-58	-71	-76	-74	-69	-80	-79	-82	-50	-49	-67	-79	-47	-19	-80	-55
Househ.	Mid. apart.	-34	-52	-38	-48	-50	-43	-37	-64	-61	-60	-52	-43	-55	-50	-39	-58	-81	-67
	Single house	-64	-72	-44	-73	-50	-44	-76	-64	-56	-74	-90	-32	-74	-52	-35	-83	-54	-43
Public investor	Hospital	-10	-29	-40	-28	-27	-32	-22	-23	-29	-13	-22	-21	-22	-22	-25	-18	-27	-30
	Sec. school	-15	-65	-70	-57	-57	-54	-47	-61	-63	-74	-79	-90	-88	-87	-75	-80	-73	-71
SIMPLE PAYBACK (YEARS)																			
										Legend									
										<= 10	> 10 & < 30	= 30							
	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	
Private investor	Large office	27	24	15	20	17	17	22	10	30	9	19	19	14	11	13	17	7	20
	Small hotel	10	13	10	11	10	7	14	7	24	7	11	9	10	8	7	12	8	19
	Strip mall	10	10	8	11	8	6	13	7	18	6	6	3	7	6	3	7	5	17
Househ.	Mid. apart.	25	9	8	9	9	9	15	10	28	7	5	4	5	6	5	5	4	16
	Single house	18	8	7	9	8	9	11	10	28	9	5	5	5	6	5	6	7	19
Public investor	Hospital	18	10	6	9	7	7	12	7	16	11	10	7	9	7	7	12	6	16
	Sec. school	30	18	12	17	13	14	21	10	23	8	14	14	11	8	11	12	7	19

SIZING RULE "MINIMUM BILL"																			
RETROFIT										NEW CONSTRUCTION									
ENERGY BILL VARIATION (% , relative to baseline)																			
										Legend									
										< -20	>= -20 & < 0	> =0							
	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	
Private investor	Large office	-16	-36	-44	-33	-24	-34	-26	-31	-32	-17	-29	-25	-23	-17	-24	-18	-27	-28
	Small hotel	-26	-44	-48	-34	-34	-33	-32	-42	-42	-56	-61	-61	-58	-60	-54	-58	-66	-70
	Strip mall	-61	-81	-85	-76	-81	-74	-73	-80	-84	-84	-90	-95	-95	-98	-86	-88	-80	-59
Househ.	Mid. apart.	-34	-63	-44	-55	-55	-54	-42	-76	-65	-60	-67	-53	-63	-60	-60	-64	-92	-71
	Single house	-64	-83	-62	-80	-74	-64	-80	-74	-59	-74	-91	-75	-81	-85	-64	-87	-65	-46
Public investor	Hospital	-12	-39	-46	-33	-28	-36	-24	-28	-33	-15	-34	-34	-29	-23	-31	-22	-32	-34
	Sec. school	-15	-65	-73	-60	-60	-59	-52	-61	-67	-74	-82	-90	-88	-95	-78	-84	-73	-73
SIMPLE PAYBACK (YEARS)																			
										Legend									
										<= 10	> 10 & < 30	= 30							
	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	
Private investor	Large office	27	26	27	28	28	23	30	10	30	11	23	30	25	26	24	30	8	26
	Small hotel	11	13	17	18	13	9	22	7	26	7	11	13	12	11	7	13	8	21
	Strip mall	10	10	11	12	9	6	16	7	20	6	9	8	8	6	5	8	5	20
Househ.	Mid. apartment	30	29	13	30	23	14	30	20	30	13	26	8	24	12	10	10	8	30
	Single house	23	17	11	18	18	19	21	19	30	11	8	8	13	9	16	9	11	30
Public investor	Hospital	25	12	14	12	11	11	24	8	23	13	11	18	12	13	11	24	7	20
	Sec. school	30	18	16	18	16	15	24	10	25	8	15	14	11	9	13	13	7	21

³¹ The simple payback is the profitability KPI used in the precedent report. This KPI is less accurate than the IRR, since the cashflows used in its calculation are not discounted (consequently, it does not consider the time value of money, nor the inflation). Note that the simple paybacks calculated by EMSF are upper bounded at the lifetime of the project (30 years)

Part V: Making sense of it all

Building on our previous research, this report provides new insights into considering decarbonization package investments in buildings and some reasons to think differently.

Trade-off strategy for decarbonization projects in buildings

Thanks to the use of a simple scatter plot displaying:

- The internal rate of return, the CO2 reduction, and the bill reduction of decarbonization project options (PV and battery sizes)
- The hurdle rate of the project for a given use case (investor profile, building segment, retrofit, or new construction),

we were able to draw :

- some generic conclusions about the relationship between PV, battery sizing, and the key output of the projects (IRR, CO2 reduction, bill reduction)
- some estimates of the viability of 5 illustrative projects in front of a given hurdle rate and IRRs for a set of 126 various projects considering one illustrative multi-criteria sizing approach (IRR, bill reduction).

Key findings:

1. There is no single investor profile given the diversity of primary or combined objectives (e.g., there are significant differences between a city investing in a public hospital, a citizen investing in the renovation of his privately owned house, or a Real Estate investment for lending an office). The overall equation of an investor may cover one or all of the following: profitability, energy bill reduction, CO2 emission reduction, maximum peak load, maximum CAPEX, expected green rental or green asset premium, or other non-financial value (e.g., welfare).

2. Estimating hurdle rates ensures a fair profitability assessment for deploying a decarbonization package. Our takeaway is that it is a complex task, as hurdle rates depend on the profile of each specific investor's profile.

Furthermore, project risks may be factored in the project hurdle rate and/or cash flows depending on the practice. In some investment cases, though, the hurdle rate may not be the primary parameter looked at, as for a company committed to decarbonizing its building portfolio "whatever it costs" or for an individual investor in a newly built single house, who may not consider a hurdle rate but simply the mortgage rate obtained for the construction of the house.

3. Using an **illustrative** multi-criteria sizing approach (dual IRR maximization-bill minimization strategy), we show that:

a. Low-carbon package investments are almost always valid, halving energy bills and CO2 emissions on average with reasonable payback periods.

b. The maximum PV size is selected in most use cases, as increasing the PV size generally contributes to an IRR that increases or remains stable, in addition to a bill reduction.

c. In about 60% of the use cases, the bill reductions achieved with the battery increments are limited compared to the required CAPEX and replacement costs, leading to a declining IRR. These include all residential use cases. However, in 40 % of all use cases, the battery is attractive regarding bill reduction and IRR. This is due to specific characteristics of the corresponding grid tariffs that make the battery particularly useful (e.g., wide spread of the energy purchase prices, unattractive sellback prices, or high weight of the power component in the bill).

d. Simple paybacks are typically improved by an average of 5 years compared to a previously tested strategy only aiming at bill minimization (which led to oversizing the battery).

Exhibit 26. Simple payback comparison between our previous report (rule "minimum bill") and with the new designed sizing rule ("mixed IRR – bill"), for the 126 use cases under study.

SIZING RULE "MIXED IRR - BILL"																																							
RETROFIT										NEW CONSTRUCTION																													
SIMPLE PAYBACK (YEARS)										Legend																													
										<= 10										> 10 & < 30										= 30									
		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S																				
Private investor	Large office	27	24	15	20	17	17	22	10	30	9	19	19	14	11	13	17	7	20																				
	Small hotel	10	13	10	11	10	7	14	7	24	7	11	9	10	8	7	12	8	19																				
	Strip mall	10	10	8	11	8	6	13	7	18	6	6	3	7	6	3	7	5	17																				
Househ.	Mid. apart.	25	9	8	9	9	9	15	10	28	7	5	4	5	6	5	5	4	16																				
	Single house	18	8	7	9	8	9	11	10	28	9	5	5	5	6	5	6	7	19																				
Public investor	Hospital	18	10	6	9	7	7	12	7	16	11	10	7	9	7	7	12	6	16																				
	Sec. school	30	18	12	17	13	14	21	10	23	8	14	14	11	8	11	12	7	19																				

SIZING RULE "MINIMUM BILL"																																							
RETROFIT										NEW CONSTRUCTION																													
SIMPLE PAYBACK (YEARS)										Legend																													
										<= 10										> 10 & < 30										= 30									
		Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S	Canada	China	Denmark	France	Italy	Spain	USA NE	USA W	USA S																				
Private investor	Large office	27	26	27	28	28	23	30	10	30	11	23	30	25	26	24	30	8	26																				
	Small hotel	11	13	17	18	13	9	22	7	26	7	11	13	12	11	7	13	8	21																				
	Strip mall	10	10	11	12	9	6	16	7	20	6	9	8	8	6	5	8	5	20																				
Househ.	Mid. apartment	30	29	13	30	23	14	30	20	30	13	26	8	24	12	10	10	8	30																				
	Single house	23	17	11	18	18	19	21	19	30	11	8	8	13	9	16	9	11	30																				
Public investor	Hospital	25	12	14	12	11	11	24	8	23	13	11	18	12	13	11	24	7	20																				
	Sec. school	30	18	16	18	16	15	24	10	25	8	15	14	11	9	13	13	7	21																				

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4. Looking at the combined overall profitability, energy bill reduction, and CO₂ emissions reduction for a selection of 5 investment cases (each with a given targeted hurdle rate), we show that there is no “one size fits all” in microgrid design when it comes to PV and battery sizing; the procedure should be adapted to the investor specificities and concerns.

5. Finally, we also investigated the potential grid burden issue appearing after deployment of the low-carbon package in the retrofit use cases. As for previous research, import peak issues caused by the battery operation can be resolved using a grid power limit condition in the battery dispatch algorithm. Import peak issues caused by the heat pump can be alleviated by deploying a PV system and a battery with grid power limit control. However, the problem cannot be completely suppressed in a few use cases (10 out of 63 retrofit use cases, mostly affecting the residential segments).

Ways to improve the analysis should include testing sensitivities against retail electricity tariff structures and technology costs and performance, both of which have improved since 2021 (the reference year for costs and prices used in this research).

How to reasonably account for risks when evaluating decarbonization investment

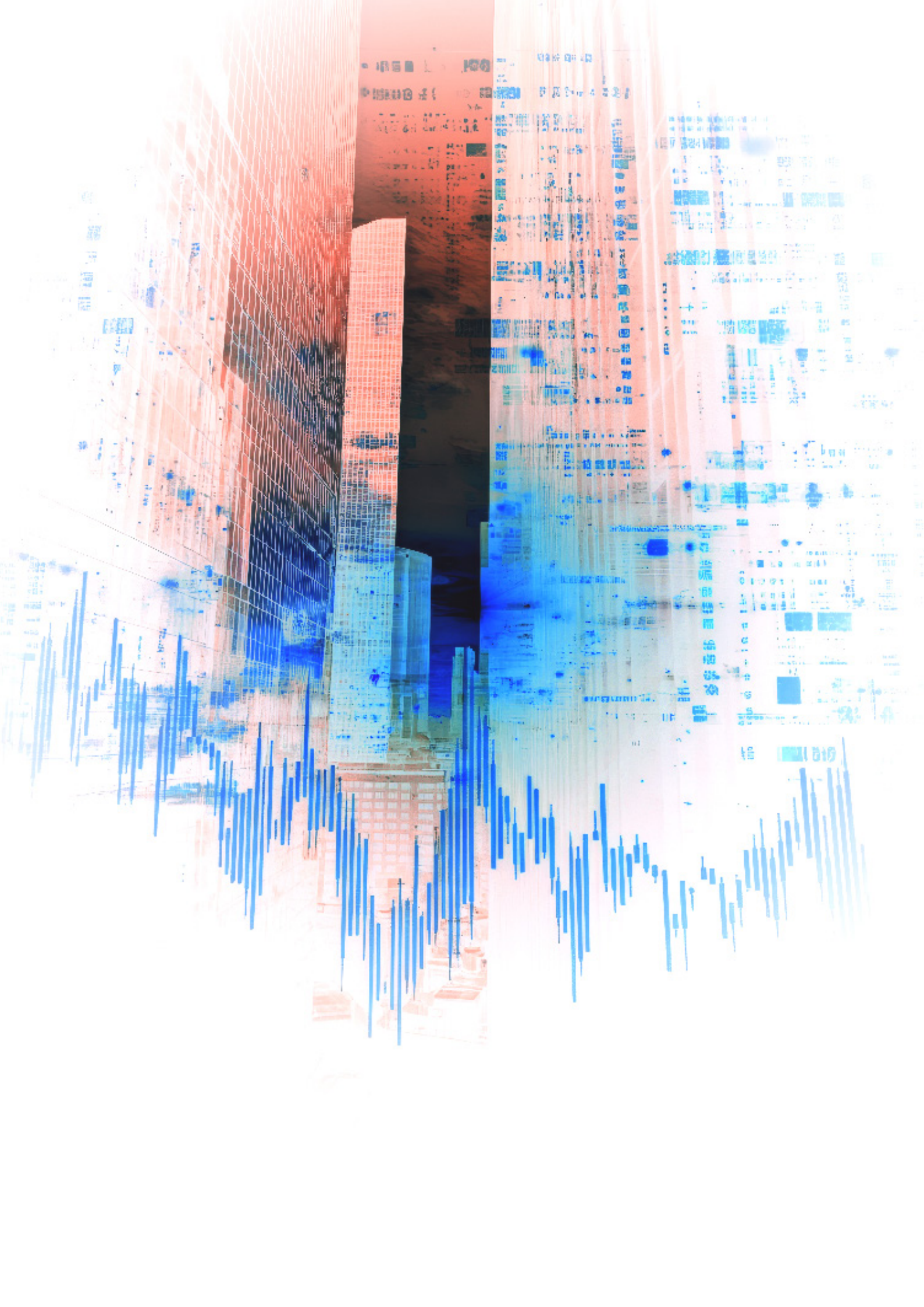
We highlighted in this research the paramount effect of the hurdle rate on profitability and, more broadly, the challenge of assessing as best as possible future cash flows (e.g., green value benefits, future penalties, or sensitivity to evolving electricity or CO₂ prices).

Setting a hurdle rate for sustainable investments has been controversial over the last two decades, and financial markets have not factored it in yet. Different views on the time preference between current and future generations are at the heart of the debate (Schoenmaker, 2024); still, there is hope. Recently, an MIT study pointed out that ESG-friendly companies could see a downward adjustment in their cost of capital by 25 basis points to 100 basis points. Companies targeting green operations should be able to attract a lower cost of debt from ESG funds; consequently, capturing this effect directly in the discount rate would be appropriate (Singh, 2022).

Recently, Bruegel, the Brussels-based economic think tank, pointed out the lack of an attractive investment case in the EU due to substantial barriers (Bruegel, 2024) such as difficult access to financing for small businesses and households, high upfront costs, split incentives in rented assets, etc. Some researchers are trying to value the broader benefits of decarbonization investments, such as the value of resilience (outage avoidance), CO₂ avoidance, health improvement, or job creation. Quantifying cash flows and value is a first step toward encouraging financial markets to factor this into their products. (NREL, 2022). Also, governments make continuous efforts to help investors make better informed decisions by massifying data, providing evidence of value creation and profitability (EC, 2024), and providing awareness of financial schemes (DOE, 2024).

Overall, the cost of capital should go down for ESG-related investment, the asset value should go up (and be taken into account), and the cash flows should improve. Hence, payback should decrease further.

In the meantime, we hope this research contributes to increasing confidence in building decarbonization investment decisions.



Annex



Thomas Edison

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Basic notions of profitability

The following paragraphs provide definitions for the profitability related KPIs used throughout this document. These definitions are based on the manual (Short, Packey, & Holt, 1995).

Inflation models the change of prices in goods and services over time. For instance, let us suppose that a certain transaction requires a cashflow CF in the present (i.e., in year 0). If we assume a constant inflation rate i^{32} , we can deduce that in n years the same transaction will lead to a cashflow equal to:

$$CF \times (1 + i)^n$$

On another note, when evaluating cashflows it is necessary to consider the “time value”: i.e., the fact that ten dollars received today are worth more than ten dollars received later the future, because the ten dollars received today can be immediately invested and yield interests. Discount rates are typically used to model this phenomenon and allow to calculate the equivalent present value of future cashflows, to be able to compare them in a fair manner. For instance, let us take the cashflow for year n previously calculated ($CF \times (1+i)^n$). Assuming a constant nominal discount rate d_n , the present value of such cashflow can be calculated as:

$$PV = CF \times \frac{(1 + i)^n}{(1 + d_n)^n}$$

Therefore, the present value of a future cashflow increases if the inflation rate is increased, but it decreases if the nominal discount rate is increased³³.

It should be kept in mind that, in the previous equations, CF is a cashflow expressed in present dollars. To compute the cashflow that the same transaction will produce in n years, we multiply it by $(1+i)^n$ (this is equivalent to expressing the cashflow in “dollars of year n”). Finally, we can compute the equivalent present value of that future cashflow by dividing it by $(1+d_n)^n$.

The present value calculation can be simplified if we define an additional rate, d_r :

$$PV = CF \times \frac{(1 + i)^n}{(1 + d_n)^n} = CF \times \frac{1}{(1 + d_r)^n}$$

This rate is known as the real discount rate, and is equal to:

$$d_r = \frac{1 + d_n}{1 + i} - 1 = \frac{d_n - i}{1 + i}$$

Net present cost (NPC)

The net present cost is a KPI in which the present value of all the cashflows of a project are calculated and summed together (cashflows corresponding to costs are positive and those corresponding to incomes are negative).

$$NPC = CF_{year\ 0} + \frac{CF_{year\ 1}}{(1 + d_r)^1} + \frac{CF_{year\ 2}}{(1 + d_r)^2} + \dots + \frac{CF_{year\ N}}{(1 + d_r)^N}$$

In the above expression, $CF_{year\ n}$ is the net cashflow of year n, calculated as costs minus incomes and expressed in present dollars (since the inflation is already accounted for in d_r). N is the lifetime of the project in years.

Here below is an NPC calculation example, for an investment project like the ones addressed in this report. In year 0, there is an investment cost (term CAPEX), to pay for the assets installed for the project (e.g., BMS, heat pump, microgrid). Every year, these assets lead to operational expenditures (term Annual OPEX), to pay for their maintenance for instance. But the assets also yield incomes (term Annual incomes), which in the projects addressed in this report are the energy bill savings. There might also be replacement costs at some points of the project lifetime (term Replacement in year j). Finally, the installed assets can be sold at the end of the project for their salvage value (term Salvage in year N).

$$NPC = CAPEX + \frac{Annual\ OPEX - Annual\ incomes}{(1 + d_r)^1} + \frac{Annual\ OPEX - Annual\ incomes}{(1 + d_r)^2} + \dots + \frac{Annual\ OPEX - Annual\ incomes + Replacement}{(1 + d_r)^j} + \dots + \frac{Annual\ OPEX - Annual\ incomes - Salvage}{(1 + d_r)^N}$$

Note that in an NPC calculation, we should only include the cashflows related to the investments being evaluated. For instance, for the projects addressed in this report, we include the costs associated to the low-carbon technologies installed (BMS, heat pump, microgrid). Consequently, we also include the bill savings enabled by these technologies. However, we do not include the costs that existed in each building prior to the installation of such technologies (e.g., the initial energy bill).

³² Note that i, and the other rates used here are annual rates (but analogous calculations can be done with monthly rates, weekly rates etc.).

³³ For plausible values of the inflation rate and of the nominal discount rate (i.e., i within [-100%, 100%] and d_n within [0, 100%]).

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A negative NPC indicates that the returns of the project are worth more than the costs, and the investment is therefore economically viable. A positive NPC indicates the opposite, that the returns are worth less than the costs.

Note that, in an NPC calculation, increasing the inflation rate causes an increase of the relative weight of later cashflows over sooner cashflows³⁴. Conversely, increasing the nominal discount rate causes an increase of the relative weight of sooner cashflows over later cashflows. Among the sooner cashflows, the CAPEX typically stands out.

Internal rate of return (IRR)

The internal rate of return is the value of the discount rate that makes the NPC of a project equal to 0, that is, right at the point where the returns of the project are worth the same as the costs.

In theory, there are two different internal rates of return:

- The real IRR corresponds to the real discount rate that sets the NPC equal to zero, i.e.,

$$IRR_r = \{d_r | NPC = 0\}$$

- The nominal IRR is the nominal discount rate that sets the NPC equal to zero. Therefore, its calculation requires assuming a value for the inflation rate, which is avoided with the real IRR.

$$IRR_n = \{d_n | NPC = 0\}$$

Unless stated otherwise, the IRR provided in this report are expressed in real terms (and not nominal). Note also that the real IRR values delivered by EMSF are lower bounded at 0.

Discounted payback

The discounted payback is the minimum number of years required for the cumulated net present cost of the project to become 0:

$$Discounted\ payback = \{j | CF_{year\ 0} + \sum_{n=1}^j \frac{CF_{year\ j}}{(1 + d_r)^j} = 0\}$$

In practice, the discounted payback indicates how much time is necessary for the net savings of the project to compensate the investment cost of year 0, plus de potential replacement costs.

In EMSF, the discounted payback is lower bounded at 0 and upper bounded at the number of lifetime years of each project.

Practical use and relation between KPIs

There are several aspects to consider when using the profitability KPIs defined above:

- A discount rate is a measure of the “time value” which can greatly vary from one investor to another, as it depends on the context of the investor (type of investor, conditions of access to capital, etc.) and on the specific context of the project being evaluated (expected risk, planned horizon, etc.).

For industrial and commercial investors, a typical guideline is to select a discount rate equal to the minimum acceptable rate of return (typically called the “hurdle rate”). In this case, it is common for a company to select a discount rate equal to its weighted average cost of capital (WACC). The reasoning behind this guideline is that the WACC³⁵ is representative of the “opportunity cost of capital” (that is, the typical returns of alternative investments within the company’s reach).

- Both the calculation of the NPC and of the discounted payback require defining a hurdle rate for the project. This is avoided with the calculation of the real IRR, but to extract useful conclusions, this KPI is compared to the hurdle rate of the project à posteriori (i.e., an IRR greater than the project hurdle rate means that it is viable, and vice versa).

- Both the real IRR and the discounted payback are normalized with respect to the size of the initial investment of the project. Therefore, they are suitable to compare investment opportunities of different nature and sizes (one of the reasons why IRR is selected as the main profitability KPI for this report, since the studied building segments require vastly different investment sizes). However, when assessing a precise opportunity, it is necessary to combine the use of these normalized KPIs with other non-normalized KPIs, such as the NPC or the total CAPEX, which inform about the size of the investment.

- In fact, although the three KPIs mentioned above measure profitability, they do not provide the same information. Consequently, each investor must choose the best suited KPI to his objectives (Chatams International, s.d.). It is also possible to use several of them in a complementary way.

³⁴ For positive values of the inflation rate.

³⁵ Average rate at which a company pays for its own sources of capital (equity and debt)

Grid burden

The installation of a heat pump and/or a battery may lead to high grid import peaks (this is what we call “grid import burden”). Such peaks might be problematic for a retrofitted building, assuming that the new equipment must be compatible with the maximum power allowed in the connection of the building to the grid (also known as “installed power”). We can suppose that, whenever such maximum power is exceeded, the protection relays trip and disconnect the building from the grid to avoid an overload. In consequence, the grid burden must be minimized or even suppressed, especially in buildings where the continuity of supply is key (e.g., hospitals). Otherwise, an increase of the installed power would be required, which is costly and not always possible if the upstream grid is stressed³⁶.

We have evaluated, for every retrofit use case and every PV/battery size, the grid imports that exceed the maximum grid power of the site. This maximum power is assumed to be 1.2 times the peak import power of the baseline simulation, i.e., prior to the implementation of the low-carbon technology package. More precisely, we have studied 1) the ratio between the peak import power and the maximum grid power; and 2) the total time in a year in which the import power is greater than the maximum grid power³⁷. Exhibit 27 provides a synthetic view of how these quantities evolve with the installation of the heat pump, the battery and the PV system, and when a grid power limit objective is introduced in the battery dispatch algorithm³⁸. For the sake of simplicity, only the results obtained with a 100% size battery and a 100% size PV are displayed³⁹.

Exhibit 27. Summary of retrofit use cases with grid import burden issues. *The peak import power is expressed as a percentage of the maximum grid power defined for each use case.

Country	Segment	BMS + heat pump		BMS + heat pump + 100% battery		BMS + heat pump + 100% battery + 100% PV		BMS + heat pump + 100% battery + 100% PV + grid limit objective in control		Cause
		Peak import power (%)	Hours per year of import burd.	Peak import power (%)	Hours per year of import burd.	Peak import power (%)	Hours per year of import burd.	Peak import power (%)	Hours per year of import burd.	
DenmarkAll	Single house	182	1068	333	1302	333	805	182	208	Heat pump, batt
USANortheast	Single house	182	1068	246	1392	246	1039	182	207	Heat pump, batt
FranceAll	Single house	164	384	221	1550	221	626	148	54	Heat pump, batt
SpainAll	Single house	164	384	202	845	171	314	148	54	Heat pump, batt
ChinaEastern	Single house	164	384	180	678	180	513	148	54	Heat pump, batt
DenmarkAll	Mid. apartment	155	148	260	480	260	312	155	39	Heat pump, batt
USANortheast	Mid. apartment	155	148	249	560	249	408	155	39	Heat pump, batt
FranceAll	Mid. apartment	117	9	157	340	157	313	100	0	Heat pump, batt
SpainAll	Mid. apartment	117	9	128	129	118	61	100	0	Heat pump, batt
ChinaEastern	Mid. apartment	117	9	121	42	121	42	100	0	Heat pump, batt
CanadaAll	Single house	287	1918	287	1923	282	1408	285	798	Heat pump
CanadaAll	Mid. apartment	280	1167	280	1166	278	977	278	426	Heat pump
CanadaAll	Secondary school	231	331	171	460	165	306	229	57	Heat pump
CanadaAll	Strip mall	125	20	86	0	71	0	70	0	Heat pump
ItalyAll	Single house	116	37	116	37	116	28	100	0	Heat pump
DenmarkAll	Secondary school	103	1	127	64	127	13	100	0	Battery
USAWest	Single house	86	0	142	2	142	1	95	0	Battery
USASouth	Single house	84	0	120	112	97	0	97	0	Battery
USAWest	Mid. apartment	78	0	162	469	155	81	100	0	Battery
DenmarkAll	Strip mall	78	0	145	393	142	129	100	0	Battery
DenmarkAll	Hospital	75	0	216	809	212	803	100	0	Battery
DenmarkAll	Small hotel	73	0	170	757	170	682	100	0	Battery
ItalyAll	Hospital	73	0	190	483	189	485	100	0	Battery
USASouth	Mid. apartment	72	0	116	80	98	0	98	0	Battery
ChinaEastern	Hospital	72	0	108	128	108	137	100	0	Battery
DenmarkAll	Large office	72	0	142	292	140	286	100	0	Battery
ItalyAll	Large office	62	0	110	132	110	123	100	0	Battery

The battery alone provokes grid burden issues in 12 out of 63 retrofit use cases (where Denmark stands out with five segments concerned), because it imports energy from the grid when the purchase price is low. The worst grid import burden caused by the battery alone is seen in the Denmark hospital use case, where a 100% size battery makes the imports exceed the maximum grid power during 809 hours per year, and the peak import power reaches 216% of the maximum power.

In some of these use cases, the introduction of a PV system allows to alleviate the import burden issue (or even suppress it). This is because the PV production is directly used to feed the load of the building, or because the battery recovers excess PV production instead of importing energy from the grid. Furthermore, the introduction of the grid power limit objective in the battery control makes the import burden issue completely disappear in any of the 12 use cases (regardless of the size of the battery or of the PV system).

The heat pump provokes excessive grid imports in 15 retrofit use cases, notably in the residential segments (single house and midrise apartment, in that order). The colder the country the more important the import burden. In the Canada single house use case, for instance, the imported power exceeds the maximum power during 1918 hours per year, and there is a peak import power of 287 % of the maximum power. However, these measures amount to 384 hours and 164 % of the maximum power in the Spain single house use case, or to 37 hours and 116% in the Italy single house use case.

And the installation of a battery further worsens the grid import burden issue in most of these residential use cases. However, the battery reduces the peak import power caused by the heat pump in the Canada secondary school and strip mall use cases. This is because the battery behavior tries to reduce the power component of the bill (demand charges).

³⁶ As a reminder, in this study the cost of a potential increase of the grid connection capacity is not considered when assessing profitability.
³⁷ This time is calculated by counting the 15-minute simulation time steps in which the import power is greater than the maximum grid power.
³⁸ As explained in Box 4, the battery dispatch is achieved by means of a model predictive control algorithm that aims at minimizing the electrical bill. It is possible to configure an additional objective by which the battery also tries to keep the imported and exported power below the maximum grid power. If it is activated, this second objective takes priority over the objective of minimizing the bill.
³⁹ As in the other sections of this report, the PV size is expressed as a percentage of the tested maximum size for each use case. Same for the battery size.

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On another note, if a PV system is installed in addition to the heat pump and the battery, the import burden issue is alleviated in most of the use cases. Finally, the introduction of a power limit objective in the battery control allows to furtherly alleviate or suppress the issue. More precisely, among the 15 use cases previously mentioned, the power limit control can completely suppress the grid import burden of 4 cases where the peak caused by the heat pump is smaller than 117% (this is true even with a 40% size battery, regardless of the size of the PV system). There are 10 other use cases in which the power limit control does not achieve much reduction in the peak power but can limit the number of hours per year with excessive grid imports.

Note however that the introduction of an additional objective in the battery control may hinder its performance in terms of bill reduction, which is not assessed in this Annex.

Analogous to the grid import burden, the installation of a PV system may result in an export power that exceeds the maximum or installed power in the connection of the building to the grid (what we call "grid export burden"). As displayed in Exhibits 28, this issue only appears in the single house segment, for all geographies.

For a 100% size PV system, the peak grid export power is around 230% of the maximum grid power. The hours per year with export burden lie between 800 and 2000, depending on the solar irradiation levels of the geography concerned. In certain geographies, the introduction of a battery allows to reduce the hours with grid export burden, since part of the excess PV production is recovered by the battery.

In other geographies, the introduction of the power limit objective in the battery control also allows to reduce the hours with grid export burden. But, given the range of battery sizes explored, the export burden issue is not suppressed in any of the concerned use cases. However, grid export burden is less crucial than grid import burden, as there are PV systems capable of curtailing excess production, to avoid grid injection.

Exhibit 28. Summary of retrofit use cases with grid export burden issues. *The peak export power is expressed as a percentage of the maximum grid power defined for each use case.

Country	Segment	BMS + heat pump + 100% PV		BMS + heat pump + 100% PV + 100% battery		BMS + heat pump + 100% battery + 100% PV + grid limit objective in control		Cause
		Peak export power (%*)	Hours per year of export burd.	Peak export power (%*)	Hours per year of export burd.	Peak export power (%*)	Hours per year of export burd.	
CanadaAll	Single house	225	821	225	732	225	636	PV
ChinaEastern	Single house	228	1092	228	773	228	773	PV
DenmarkAll	Single house	239	1060	239	671	239	670	PV
FranceAll	Single house	228	1092	228	773	228	773	PV
ItalyAll	Single house	210	1113	210	907	210	907	PV
SpainAll	Single house	228	1092	228	773	228	773	PV
USANortheast	Single house	239	1060	238	967	239	829	PV
USASouth	Single house	255	2000	255	1930	255	1779	PV
USAWest	Single house	238	1836	238	1832	238	1678	PV

Exhibit 29. Scatter plots for the 126 uses cases. Apartment Midrise.

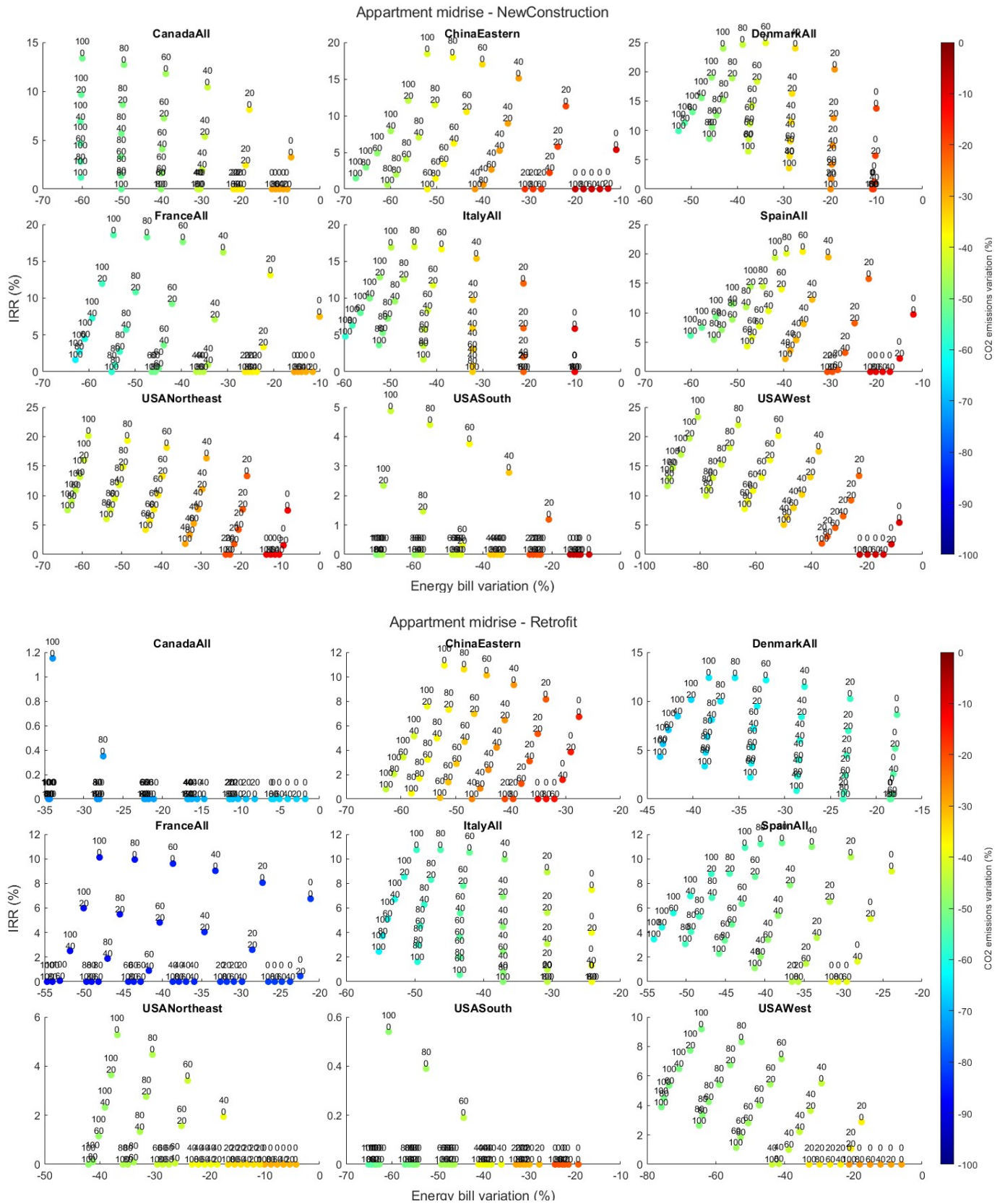


Exhibit 29. Scatter plots for the 126 uses cases. Hospital.

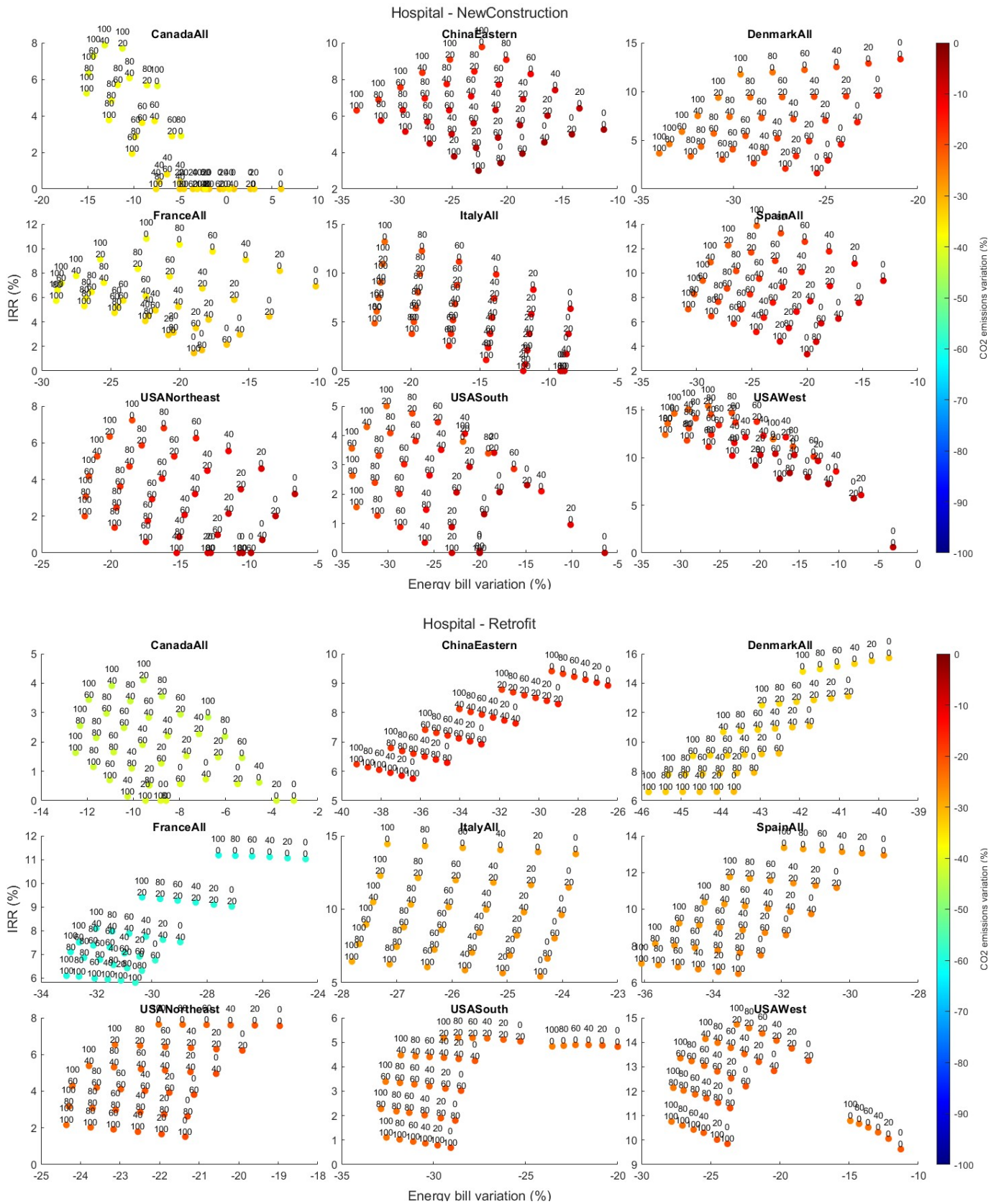


Exhibit 29. Scatter plots for the 126 uses cases. Small Hotel.

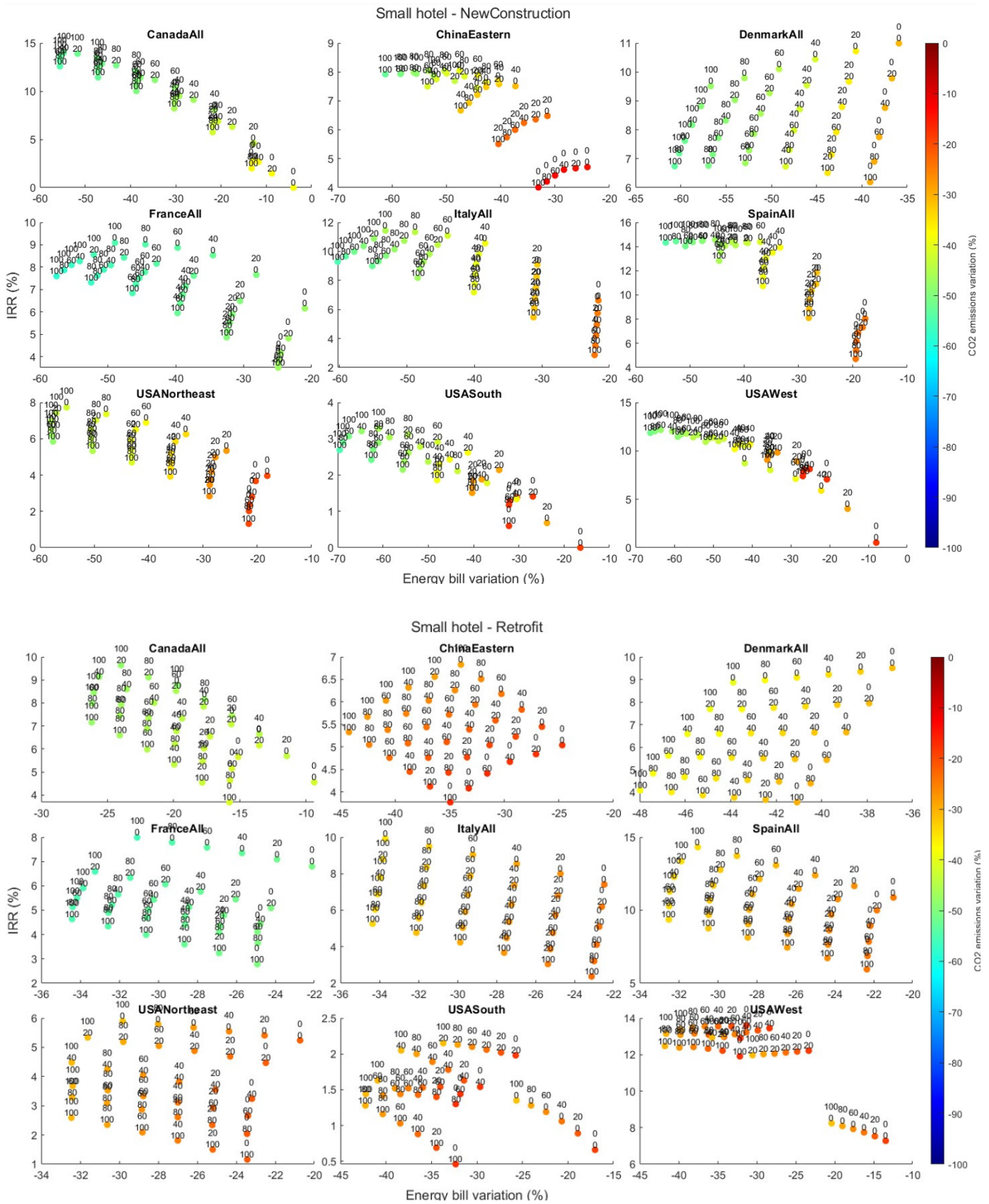


Exhibit 29. Scatter plots for the 126 uses cases. Single House.

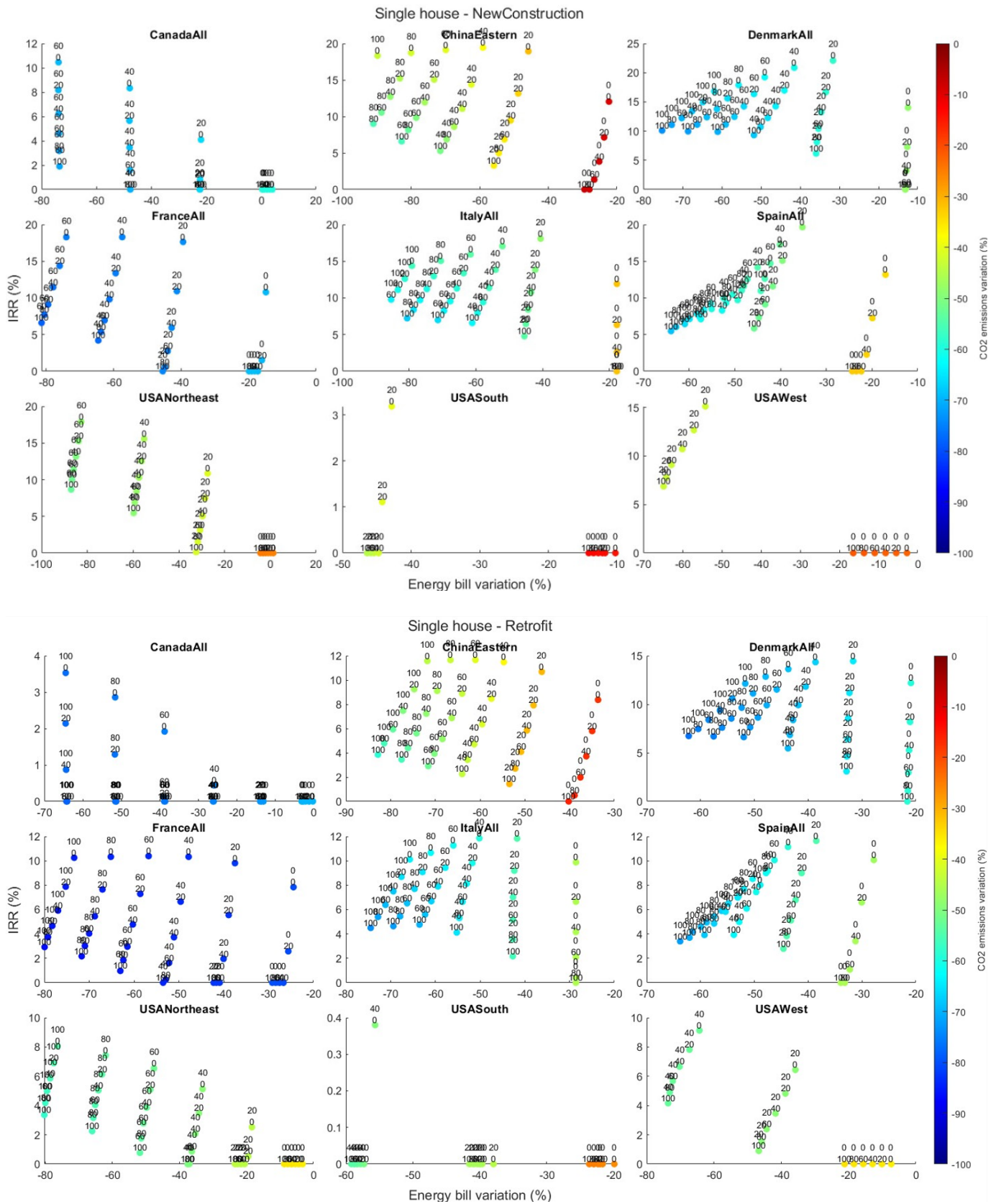


Exhibit 29. Scatter plots for the 126 uses cases. Strip Mall.

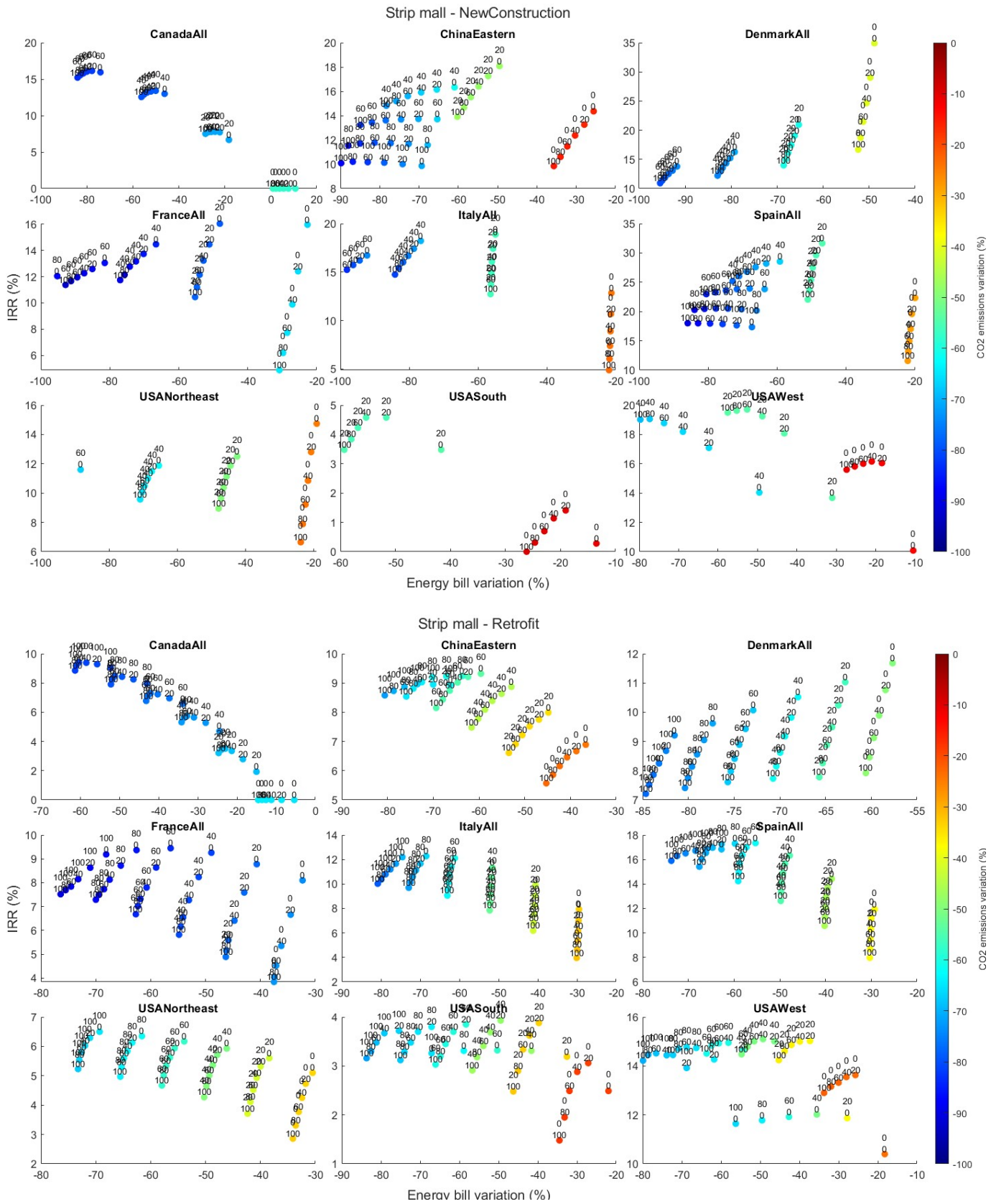


Exhibit 29. Scatter plots for the 126 uses cases. Large Office.

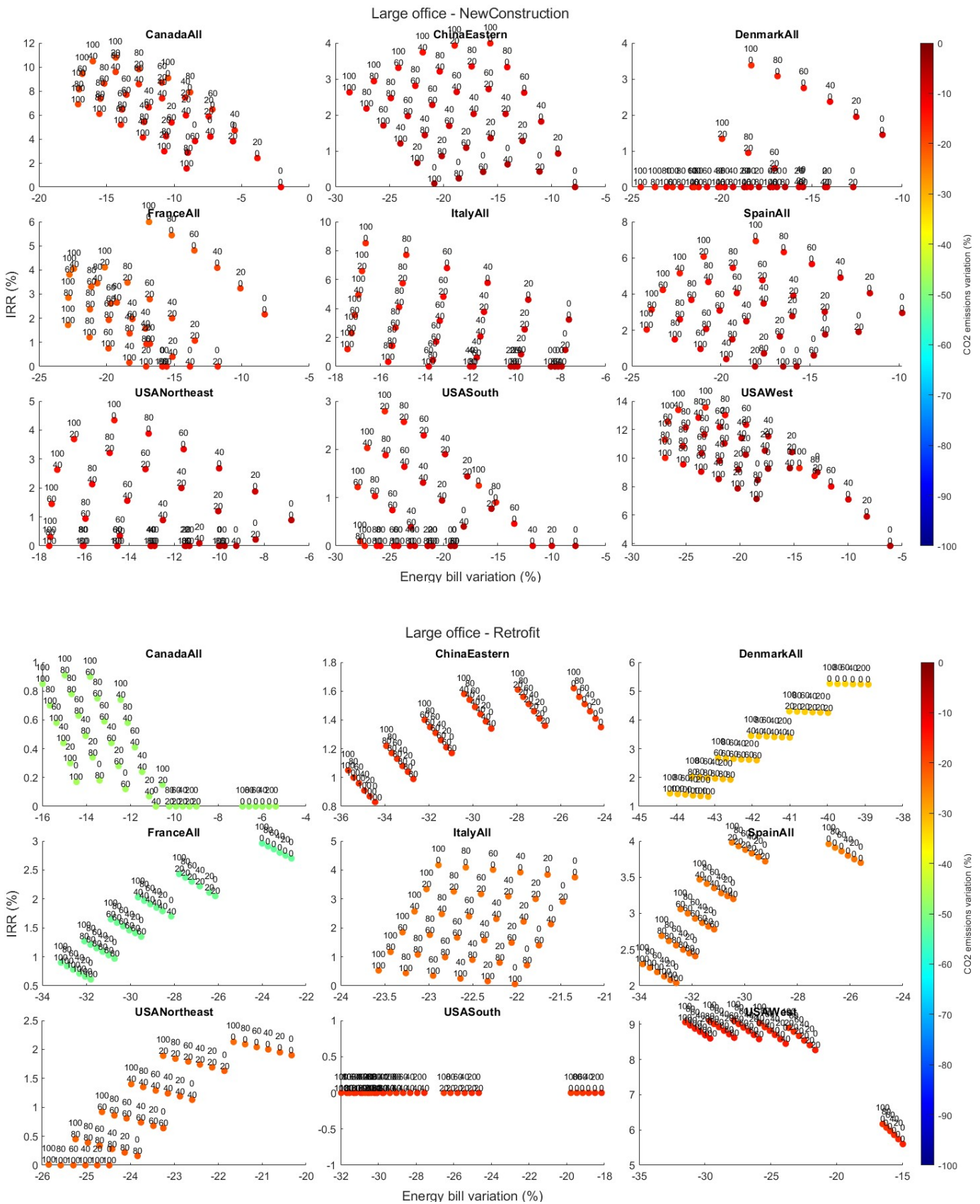
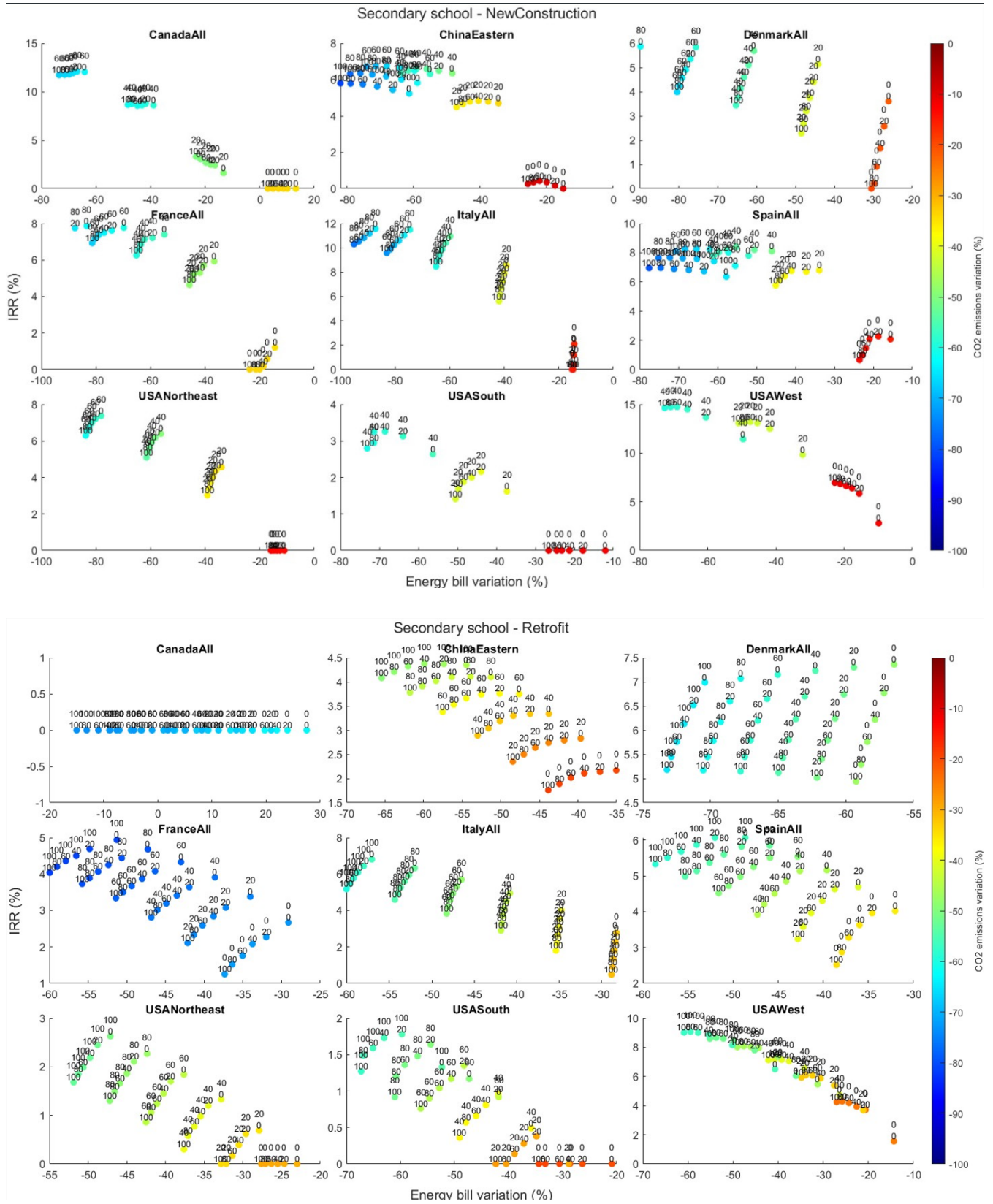


Exhibit 29. Scatter plots for the 126 uses cases. Secondary School.



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Bill decomposition of five illustrative use cases

The following exhibits display the components of the energy bill before the implementation of the low-carbon technologies («baseline») and after the implementation of the heat pump, the BMS and each of the tested PV and battery sizes. The PV and the battery sizes are given as a percentage of the maximum sizes tested in each use case.

Exhibit 30. Evolution of the components of the annual energy bill with varying PV and battery sizes, for the retrofit of a strip mall in Italy

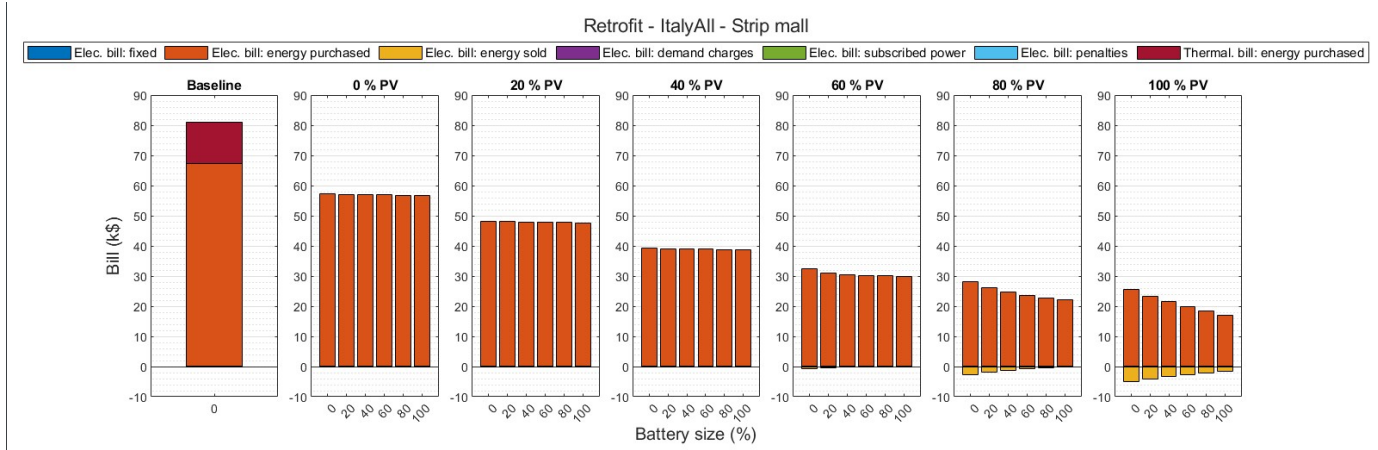


Exhibit 31. Evolution of the components of the annual energy bill with varying PV and battery sizes, for the new construction of a strip mall in China.

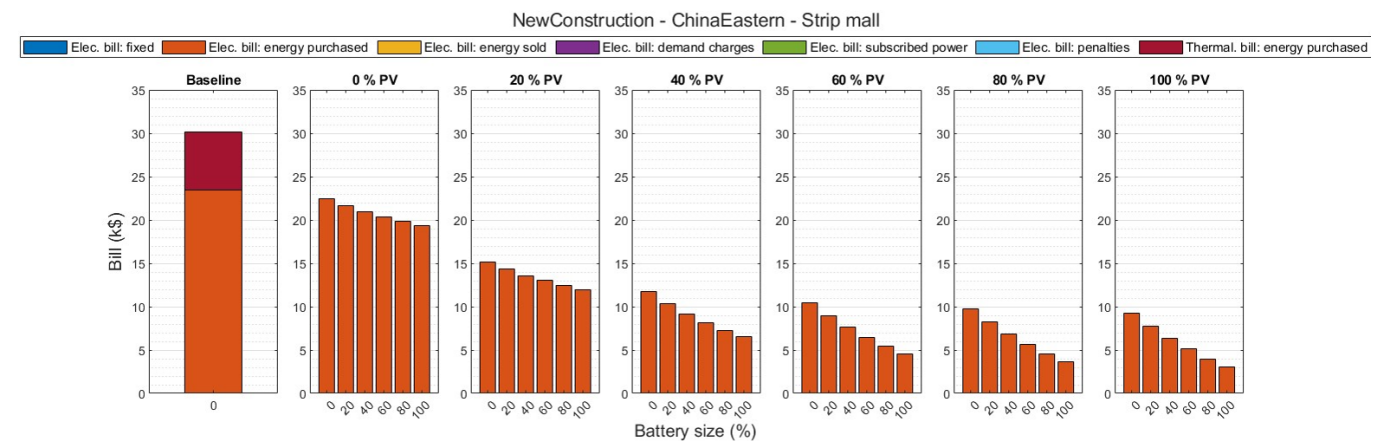


Exhibit 32. Evolution of the components of the annual energy bill with varying PV and battery sizes, for the new construction of a small hotel in Denmark

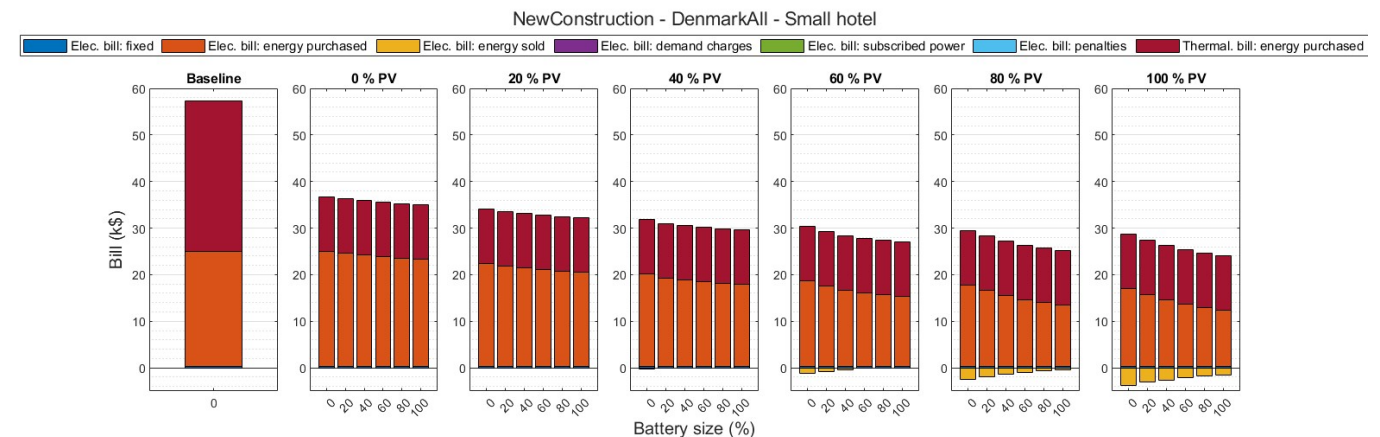


Exhibit 33. Evolution of the components of the annual energy bill with varying PV and battery sizes, for the retrofit of a hospital in USA South

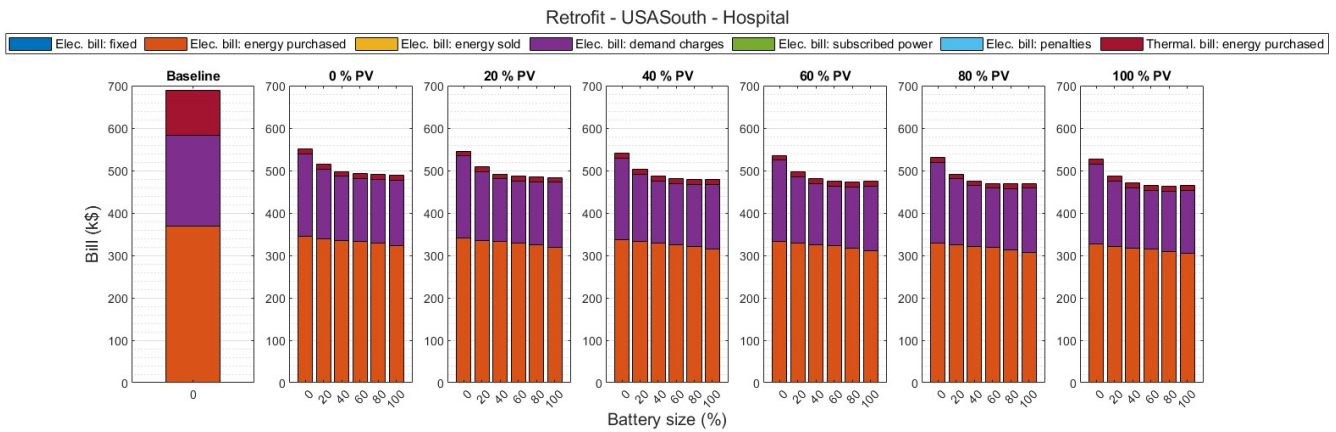


Exhibit 34. Evolution of the components of the annual energy bill with varying PV and battery sizes, for the retrofit of a house in France.

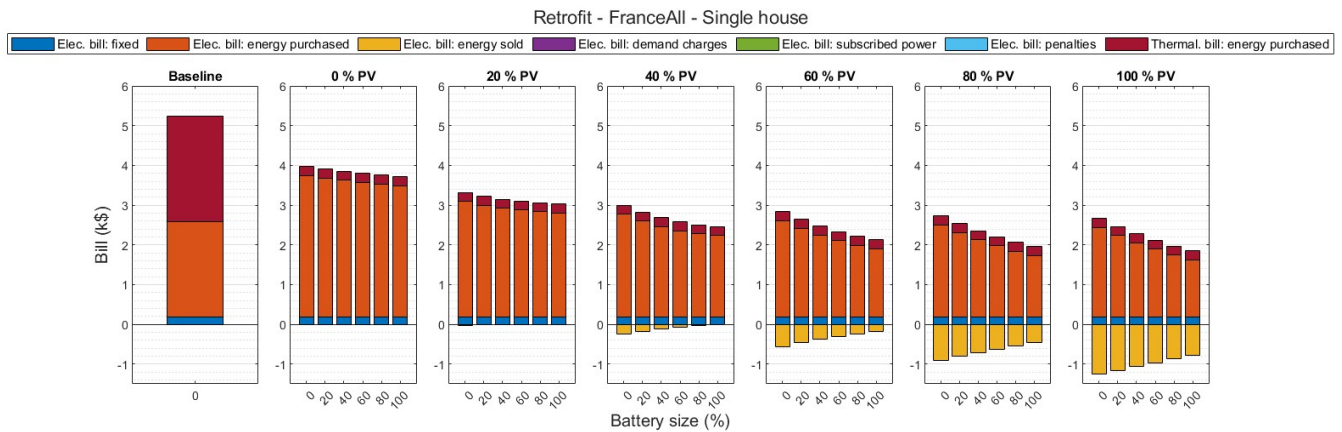
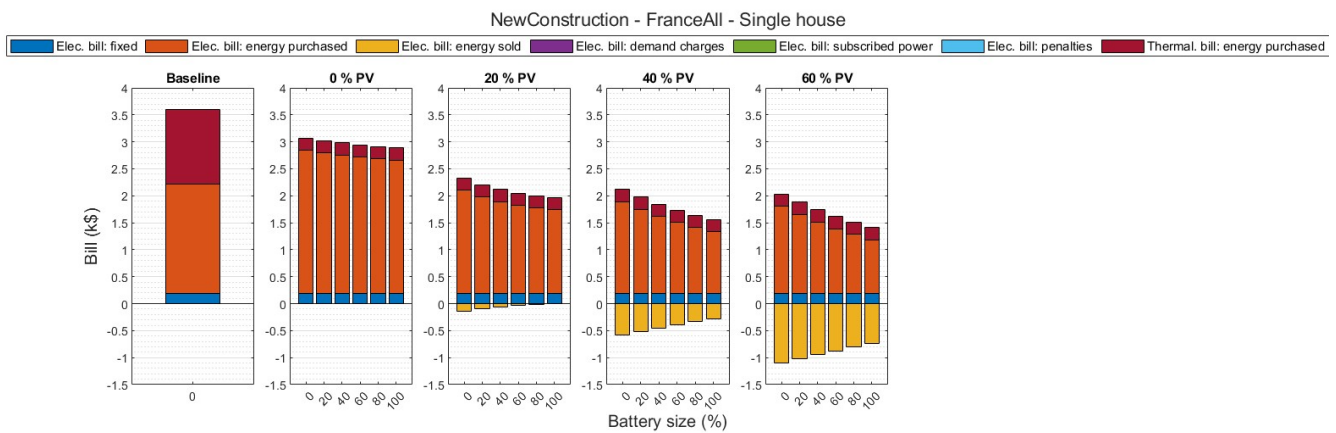


Exhibit 35. Evolution of the components of the annual energy bill with varying PV and battery sizes, for the new construction of a house in France⁴⁰.



⁴⁰NB: 80%PV and 100%PV sizing not shown because the corresponding simulations have been excluded from the sizing space.

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Acronyms and expressions

- BMS: Building management system,
- COP: Coefficient of performance
- IRR: Internal rate of return
- NPC: Net present cost
- CAPEX: Capital expenditure
- OPEX: Operational expenditure
- KPI: Key performance indicator
- PV: Photovoltaic
- EMSF: Energy management simulation framework
- MPC: Model predictive control
- Microgrid: Combination of a battery and a rooftop PV

- Use Case: combination of building age, building segment and geography.
- Case Study: combination of a Use Case and an Investor profile

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Nation states and corporations are increasingly making climate pledges and including sustainability themes in their governance. Yet, progress is nowhere near where it should be. For global society to achieve these goals, more action and speed is needed.

How can we convert momentum into reality?

By aligning action with United Nations Sustainable Development Goals. By leveraging scientific research and technology. By gaining a better understanding of the future of energy and industry, and of the social, environmental, technological, and geopolitical shifts happening all around us. By reinforcing the legislative and financial drivers that can galvanize more action. And by being clear on what the private and public sectors can do to make all this happen.

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