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Energy Efficiency and Risk Management in Public Buildings

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List of Acronyms

BMS Building energy management system

CHP Combined heat and power

CVaR Conditional value-at-risk

DER Distributed energy resources

DER-CAM DER Customer Adoption Model

DG Distributed generation

DoW Description of Work

DSS Decision support system

DV Decision variable

EnRiMa Energy Efficiency and Risk Management in Public Buildings

EPBD Energy Performance of Buildings Directive

EU European Union

FASAD Fundación Asturiana de Atención y Protección a Personas con Discapacidades y/o Dependencias

FiT Feed-in tariff

HVAC Heating, ventilation, and air conditioning

NG Natural gas

PV Photovoltaic

ST Solar thermal

ToU Time of use

VaR Value-at-risk

Executive Summary

In order to reduce energy consumption by public buildings, both short- and long-term decision support is necessary. In previous work such as Deliverables D2.2 and D7.1, we have demonstrated the powerful impact that smarter operations of installed equipment can have on energy consumption, e.g., delivering 10% savings or more. Complementary to this approach is a long-term one based on strategic decisions, viz., investment in new technologies, retrofit of the building shell, and decommissioning of installed technologies. Towards this end, the stochastic optimisation framework developed in Deliverable D4.2 and refined in D4.3 provides long-term decision support. An innovative feature of this model is the capability to handle not only uncertainty in energy prices and technology costs (thanks to the scenario generation methodology from Deliverable D3.2) but also risk management. In this deliverable, we synthesise these modelling developments to obtain managerial and policy insights about the extent of reductions in energy consumption, costs, CO_2 emissions, and risk achievable at two EU test sites (real buildings in Austria and Spain). Relative to the "do nothing" case of persisting with the current building configuration and installed equipment, we find that an optimal long-term strategy for the Spanish site, FASAD, is to invest in new CHP, PV, and solar thermal equipment over the next sixteen years. This will reduce expected costs by 17% (or, €0.5 million) over this time horizon and deliver 35% reductions in expected primary energy consumption and CO_2 emissions. By reducing exposure to volatile energy prices, the strategy also gives a nearly 20% reduction in risk. For the Austrian site, Pinkafeld, similar patterns in the metrics are observed. However, because of the site's more recent retrofit, its existing energy efficiency is high, and thus, the extent of savings is slightly lower than for FASAD. Through this framework, alternative policy settings may also be explored ("what-if" analysis), e.g., more stringent regulation on energy efficiency. Consequently, tradeoffs among competing objectives and the effectiveness of proposed regulation may be assessed via this model, thereby contributing to the project's recovery-of-investment analysis as part of Operational Objective O6 in the Description of Work. A preliminary market analysis using an epidemic model for technology diffusion is also included and serves as a basis for the development of an exploitation plan in Deliverable D7.4.

1 Introduction

The overall objective of the "Energy Efficiency and Risk Management in Public Buildings" (EnRiMa) project is to improve energy efficiency and to enable risk management in public buildings. Its expected outcomes concerning Objective EeB.ICT.2010.10-2a (ICT for energy-efficient buildings and spaces of public use) are as follows:

1. Contribution to the opening of a market for ICT-based customised solutions integrating numerous products from different vendors and offering services from design of integrated systems to the operation and maintenance phases.

2. Establishment of a collaboration framework between the ICT and buildings and construction sectors aimed at exploiting opportunities for the development of ICT-based systems in compliance with the Energy Performance of Buildings Directive (EPBD).

3. Radical reduction of energy consumption, in line with the policy framework for facilitating the transition to an energy-efficient, low-carbon economy through ICT.

Relevant to this deliverable is item 3, which pertains to Operational Objective O6 of the DoW, i.e., a recovery-of-investment analysis that quantifies reductions in energy consumption via ICT-enabled decision support at two real buildings. In particular, we focus here on Task 7.5 of the DoW: to use the EnRiMa decision support system (DSS) in advisory mode for "what-if" analysis to deliver policymaking insights concerning equipment adoption and energy-efficiency retrofits given future uncertainties in energy prices and technology costs.

Towards this end, the EnRiMa project has devised two DSS modules: an operational one and a strategic one (Fig. 1). The former is supposed to focus on short-term intra-day decisions on equipment operations and energy sourcing, e.g., how to run the installed radiators and heating, ventilation, and air condition (HVAC) systems optimally; see Deliverable D2.2 (UCL et al., 2012). At the lower level are the thermodynamic constraints on the equipment and the building physics, which are described in further detail in Groissböck et al. (2014) and illustrated via numerical examples. In particular, we show that simply by operating the installed equipment in a smarter way, it is possible to realise reductions in energy consumption for heating of at least 10%. Moreover, in Deliverable D7.1 (UCL et al., 2013), we presented an integrated operational model that fuses the lower-level operations of the conventional radiator and HVAC system with the possibilities to change the sourcing of the energy, viz., suppliers and on-site generation.

By contrast, the focus of this deliverable is the strategic DSS that deals with long-term decisions concerning investment in new technologies, decommissioning of old equipment, and retrofitting the building shell. Unlike the operational DSS, all energy demands in the strategic DSS are treated as parameters, and their seasonal variations are incorporated as

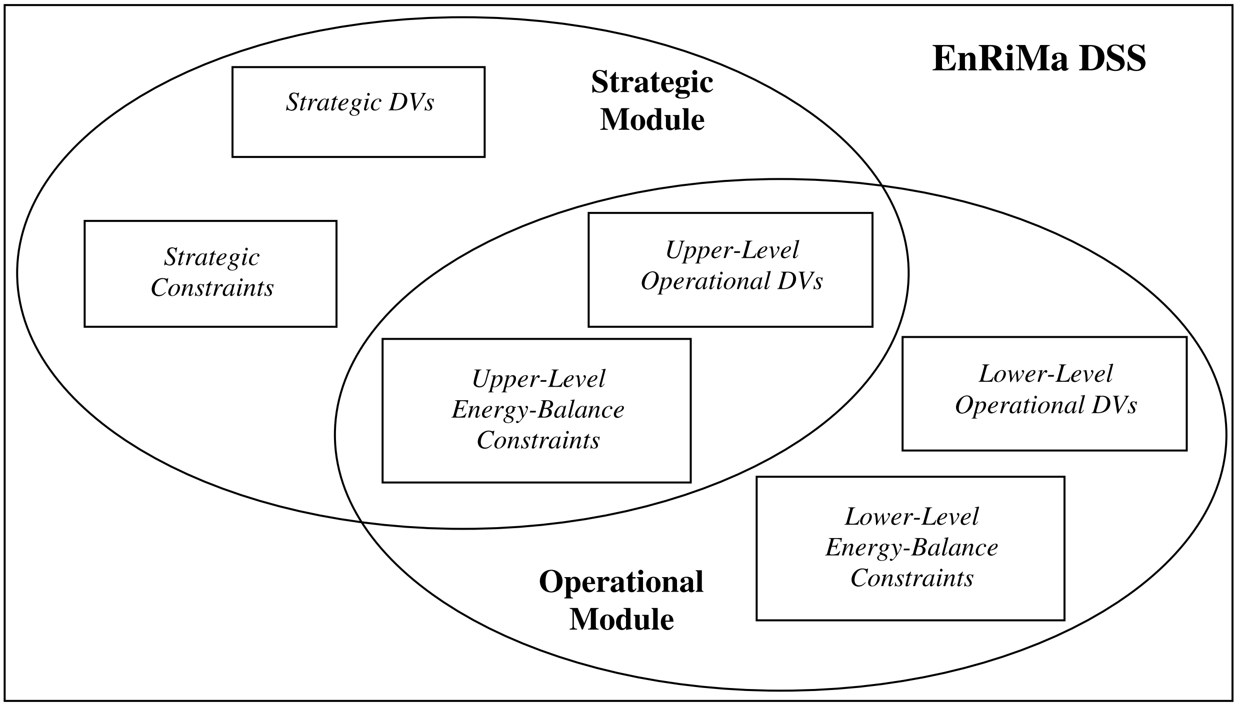

Figure 1: EnRiMa DSS Schema

profiles, e.g., different seasons or day types with appropriate weights. Thus, the strategic DSS comprises the upper-level operational constraints and decision variables (DVs) along with strategic decision variables and constraints, i.e., it contains a simplified version of the operational model. Crucially, since strategic decisions take place over a time horizon of several years or even decades, uncertainty in energy prices and technology costs cannot be ignored. In fact, given the deregulation of the energy sector and incentives for new technology development, such parameters are increasingly in flux. Exposure to such fluctuations may pose risk for building managers contemplating strategic decision making. Indeed, without adequate decision support, more risk-averse building owners may be deterred from undertaking decisions that improve energy sustainability because of the perceived downsides.

Unlike extant models for long-term decision analysis of technology investment at the building level (King and Morgan, 2007; Marnay et al., 2008), we endeavour to address not only uncertainty but also risk management. For example, Maribu and Fleten (2008) allow for uncertainty in both electricity and natural gas prices but do not treat risk endogenously. By contrast, our approach not only generates scenarios (Kaut et al., 2014) for energy prices and technology costs (Fig. 2) but also includes a coherent risk measure, the conditional value-at-risk (CVaR, Rockafellar and Uryasev (2002)), in the objective function. The scenario tree in Fig. 2 has red nodes corresponding to stages at which strategic decisions are made. Since investment decisions require information about the subsequent performance of technologies, each strategic node encapsulates a simplified operational model (represented by blue nodes). Each operational profile models energy production and consumption at each point in time for different seasons or day types. Thus, although energy balances are maintained at a high level, energy flows inside each subsystem, e.g., conventional radiators or HVAC systems, are neglected. Indeed, these are dealt with in detail by the dedicated operational model for short-term optimisation.

With the CVaR, the decision maker can specify the level of exposure to risk to control for extremely high costs by minimising the expected cost given that the cost is in the top $(1 - \alpha) \times 100\%$ of outcomes (Fig. 3). The confidence level, α, is typically chosen to be 0.95 or 0.99. Given the scenarios, energy-balance relations may be specified at each point in time (Fig. 4) to formulate a stochastic programming model for risk-averse decision making (Conejo et al., 2010). An overview of EnRiMa's strategic approach can be found in Cano et al. (2014). Deliverable D4.6 (URJC et al., 2014) contains the complete mathematical formulation of EnRiMa's strategic model.

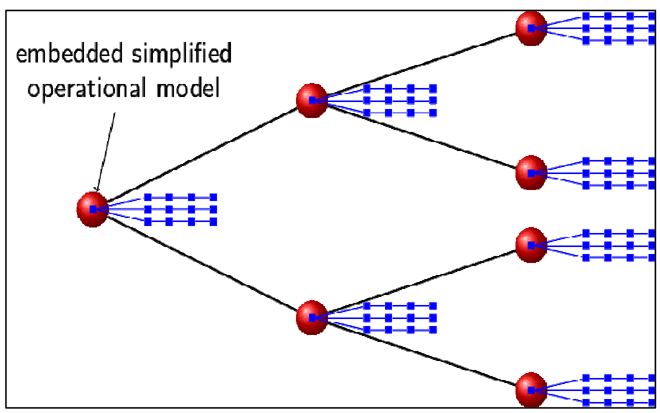

Figure 2: Scenario Generation for the EnRiMa Strategic DSS (Kaut et al., 2014)

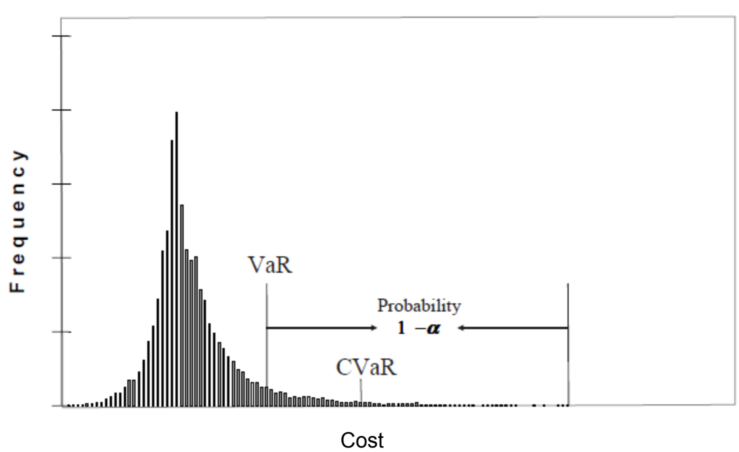

Figure 3: Conditional Value-at-Risk Illustration

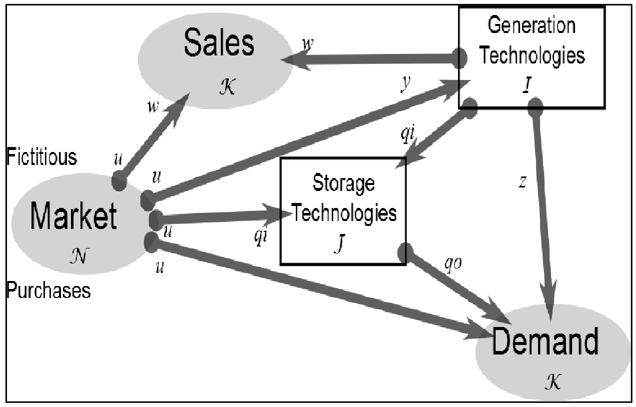

Figure 4: Energy Flows in the EnRiMa Strategic DSS

In order to fulfil the requirements of Task 7.5 and to contribute to the attainment of Operational Objective O6, this deliverable implements the EnRiMa strategic DSS for various regulatory settings in order to gain insights about the tradeoffs between expected cost reduction and CO_2 emissions mitigation or expected cost reduction and risk management, for example. These runs are performed for likely regulatory settings and implemented for the two EnRiMa test buildings: (i) Centro de Adultos La Arboleya (Siero, Spain), which belongs to the Fundación Asturiana de Atención y Protección a Personas con Discapacidades y/o Dependencias (FASAD), and (ii) Fachhochschule Burgenland's Pinkafeld campus, which is located in Pinkafeld, Austria. Hence, in contrast to the short-term focus of Deliverable D7.1 (UCL et al., 2013), the findings of this deliverable pertain to the long-term benefits that are possible for public buildings from using ICT-enabled DSS under various regulatory settings.

We demonstrate that, relative to the "do nothing" case of maintaining the *status quo* building configuration and installed equipment, expected reductions in energy consumption of 35% are possible at FASAD from using the strategic DSS. This is achieved by installing combined heat and power (CHP), photovoltaic (PV), and solar thermal (ST) equipment to reduce exposure to increasingly high and volatile energy prices. At Pinkafeld, investing in PV and ST equipment reduces expected primary energy consumption by 16%. At both sites, further energy savings can be achieved by installing energy storage equipment. By specifying alternative objective functions, higher reductions in expected CO_2 emissions and risk may be achieved, albeit by trading off some of the economic benefits. In a similar vein, more stringent regulation stipulating a significant reduction in energy consumption relative to the "do nothing" case may be attained at a much higher expected cost. In summary, implementation of the strategic model reveals how to reduce the expected cost (by 17% at FASAD and 5% at Pinkafeld) of meeting energy needs along with the expected CO_2 emissions, expected primary energy consumption, and the financial risk.

The structure of this report is as follows:

- Section 2 describes the regulatory settings under which the EnRiMa strategic DSS has been implemented.
- Section 3 presents an overview of the strategic optimisation model.
- Section 4 provides the results of numerical examples for each site after careful calibration with observed data in order to deliver policy insights.
- Section 5 summarises this report's findings and relates them to the objectives set forth in the DoW.

Appendices A, B, and C provide the mathematical formulation of the strategic optimisation model together with its nomenclature, parameter values used in the numerical examples, and a procedure for predicting technology diffusion, respectively.

2 Regulatory Settings

In order to gain policy insights about capacity expansion under uncertainty at public buildings, we first need to calibrate the EnRiMa strategic DSS. This is done by running the model for just the current year with all strategic DVs fixed. The resulting output on energy consumption, production, purchases, and sales should match the observed values from Deliverable D1.1 (HCE et al., 2011).

After this calibration step, we generate scenarios for energy prices and technology costs over the specified time horizon. We use both time-series data and expert opinion to set suitable parameter values. On the basis of these scenarios, the EnRiMa strategic DSS is run with all investment, decommissioning, and retrofitting decisions fixed to capture the future operations of existing buildings without any decision support. Metrics such as expected costs, primary energy consumption, and CO_2 emissions will be calculated along with the CVaR for cost. Such a run is subsequently referred to as the "do nothing" one and serves as the basis for comparison of the benefits of the EnRiMa strategic DSS.

Using the same generated scenarios, we then implement the EnRiMa strategic DSS with all strategic decision variables, e.g., investment, decommissioning, and retrofitting, enabled. For this baseline "invest" setting, the calculated metrics may be compared with those from the "do nothing" one in order to estimate the extent of the benefits possible. For further policy insights, e.g., in terms of understanding how new measures may enable further sustainability gains, site-specific settings are identified in consultation with local experts. Thus, for FASAD, the regulatory and market settings under consideration are the following:

- Setting 1 (baseline): flat energy tariff rates (0.1426 €/kWh_e for electricity purchases and 0.0523 €/kWh for natural gas purchases); electricity feed-in tariff[1] (FiT) for CHP

[1]Source: Special Scheme for Electricity Generation with Renewable Energy Sources (BOE, 2013).

of 0.1721 €/kWh$_e$.

- Setting 2: revocation of the FiT.
- Setting 3: a regulatory requirement that the primary energy consumption be reduced by 50% relative to the "do nothing" case.
- Setting 4: change from a flat to a time-of-use (ToU) electricity purchasing tariff (whose rate is 0.1522 €/kWh$_e$ between 7:00 and 14:00 and between 17:00 and 20:00, 0.1438 €/kWh$_e$ between 14:00 and 17:00, and 0.1336 €/kWh$_e$ otherwise).

For Pinkafeld, we examine the following regulatory and market settings:

- Setting 1 (baseline): flat energy tariff rates (0.15 €/kWh$_e$ for electricity purchases, 0.08 €/kWh$_e$ for electricity sales, and 0.08 €/kWh for district heat purchases).
- Setting 2: availability of a subsidy of 200 €/kW$_p$ and a FiT for new PV installations[2] (with a rate of 0.125 €/kWh$_e$).
- Setting 3: regulatory requirement that imposes 30% savings in primary energy consumption relative to the "do nothing" case.
- Setting 4: change from a flat to a ToU electricity purchasing tariff[3] (whose rate is 0.16 €/kWh$_e$ between 7:00 and 14:00 and between 17:00 and 20:00, 0.15 €/kWh$_e$ between 14:00 and 17:00, and 0.14 €/kWh$_e$ otherwise).

3 Strategic Model Overview

In this section, we give a brief overview of the EnRiMa strategic optimisation model. Its complete mathematical formulation is presented in Deliverable D4.6 (URJC et al., 2014). To keep this deliverable self-contained, the formulation is repeated in Appendix A.

The strategic DSS is a dynamic optimisation model for the long-term management of a public building under uncertainty. The model determines an optimal policy for investment in new technologies and decommissioning of old equipment, given that the building's energy demands must be met uninterruptedly over the planning horizon. Thus, along with strategic DVs and constraints on investments, the model comprises operational DVs and constraints that deal with energy production, storage, and procurement in order to evaluate the performance of the strategic decisions (Fig. 1). In the strategic model, the planning

[2]Source: Ökostrom-Einspeisetarifverordnung 2012 (BKA, 2013).

[3]Source: Gewerbestrom SMART tariff from Energie AG (http://www.energieag.at/eag_at/resources/339536908088248262_912154373613149818_jangqJY9.pdf). The tariff has been adjusted so that its average hourly rate is equal to the corresponding flat rate of the baseline setting.

horizon is partitioned into strategic (long-term) decision periods (e.g., with yearly time resolution), each of which accommodates many operational (short-term) decision periods (e.g., with hourly time resolution). Strategic decisions are selected at the start of each strategic period, whereas operational decisions are made during each operational period. To reduce computational complexity, we assume that strategic periods can be described by a small set of operational profiles (with assigned probabilities). For instance, the operational profiles can be a selection of typical days representing conditions during different seasons and load periods and of extreme days with particularly high load. Operational DVs and constraints for every operational period (e.g., hour) of each of these days are included in the model. Concretely, the constraints of the strategic model can be divided into the following categories:

1. **Strategic** constraints deal with strategic decisions, such as investments and contracting. These constraints keep track of the installed equipment, impose upper limits on the number of installed devices, pollution emissions, and investment cost, and guarantee that only one sales and purchasing tariff is chosen per node and energy type.

2. **Operational** constraints deal with operational decisions, such as energy trade, generation, or storage. These include the energy-balance equations, which guarantee that, for each energy type, the net energy supply must meet the energy demand (less the energy saved due to passive technologies) in each time period. The net energy supply consists of the energy produced by energy-generating technologies plus the energy discharged from storage and the energy purchases less the energy used for production or charging of storage devices and the energy sold. Also part of this constraint category are the storage balance equations, which keep an inventory of the energy available in energy-storage equipment.

3. **Strategic-operational** equations link the operational performance with the strategic decisions or policies. These constraints ensure that the technologies operate within the installed capacity limits and according to their availability (e.g., photovoltaic panels cannot produce electric energy during the night), the energy purchases and sales do not exceed the volumes stipulated in the signed energy contracts, and that minimum energy efficiency requirements are satisfied. Moreover, they guarantee that the energy charged, discharged, and stored into energy-storage devices remains within certain limits dictated by the infrastructure and chemistry of those devices.

4. **Computational** equations compute auxiliary variables to simplify the largest equations. These auxiliary variables may be reused in different equations.

5. **Aggregation** equations create aggregated values of operational decisions or parameters

per node. Those values are useful for visualisation and post-analysis purposes.

6. **Risk** constraints quantify the risk. The CVaR is used as risk measure.

7. **Mean-risk** constraints compute a weighted average of the expected value and the CVaR of either the total discounted cost, the total pollution emissions, or the total primary energy consumption.

In our strategic optimisation model, we consider a mean-risk objective function of either the total discounted cost, the total pollution emissions, or the total primary energy consumed, where the total discounted cost is composed of the discounted installation, decommissioning, maintenance, energy trading, and technology operation costs. The risk and mean-risk constraints of the metrics that are not comprised in the objective function are excluded from the optimisation model. For instance, if the total discounted cost is selected, then the goal is to minimise a weighted average of the expected value and the CVaR of the total discounted costs. The risk and mean-risk constraints involving pollution emissions and primary energy consumption are excluded from the model in this setting.

4 Numerical Results

In order to provide managerial and policy insights about capacity expansion under uncertainty at public buildings, we implement the EnRiMa strategic DSS using data from the FASAD and Pinkafeld sites. For our numerical experiments, we consider a planning horizon of sixteen years with yearly strategic and hourly operational decision intervals. For FASAD, monthly operational profiles are used, whereas one operational profile is created for each month–weekday/weekend combination for Pinkafeld. Discounting is carried out at an annual rate of 5%.

In order to account for uncertainty in energy prices and technology investment costs in the strategic model, we approximate the distribution of these random parameters by a discretisation in the form of a scenario tree that branches at stages 6 and 11 and has a branching factor of 5. This results in a total of 25 scenarios, which are generated with the scenario generator presented in Deliverable D3.2 (SINTEF et al., 2012). Historical data are used to estimate the parameters of the distribution of the energy prices and investment costs; see Tables 10 and 14 for FASAD's and Pinkafeld's parameters, respectively.

For each test site, we run the EnRiMa strategic DSS with all investment and decommissioning decisions first fixed ("do nothing" case) and then enabled ("invest" case). In addition, we investigate the impact of the regulatory settings described in Section 2 on the optimal investment solutions. For FASAD, the technologies under consideration are the following:

- Currently installed: one 1279.1 kW and one 232.6 kW natural gas-fired boiler, and one 5.5 kW_e CHP unit.
- Investment options: 5.5 kW_e CHP units, 290 kW natural gas-fired boilers, 0.245 kW_p PV panels, and 2.011 kW solar thermal (ST) collectors.

For Pinkafeld, the following equipment is considered:

- Currently installed: one 1.28 kW_p PV system and one 79.8 kW HVAC system.
- Investment options: 1.28 kW_p PV panels and 1 kW solar thermal collectors.

Moreover, for each site, we extend the "invest" case to include thermal storage as part of the investment portfolio ("invest incl. storage" case).

The main input parameters used in our numerical experiments are presented in Appendix B. All optimisation problems are solved via the EnRiMa DSS user interface (prototype V1.03) using the Solver Manager presented in Deliverable D4.6 (URJC et al., 2014). EnRiMa's strategic model is implemented as a mixed-integer linear program in the General Algebraic Modeling System (GAMS) and solved using ILOG CPLEX.

4.1 FASAD

The numerical results for FASAD with expected cost minimisation exhibit significant benefits relative to the "do nothing" situation (Table 1). The "do nothing" case resulted in an expected discounted cost over 16 years of about €3 million, which may be trimmed by €0.5 million as a result of the strategic model. By investing in CHP technology in conjunction with PV and solar thermal, it is possible to reduce the expected discounted cost by nearly 20% with 35% savings in expected primary energy consumption and CO_2 emissions. Even the risk, captured by a CVaR of €2.8 million, is reduced by nearly 20%. This means that the expected discounted cost given that it is in the top 5% of discounted costs is €2.8 million with the strategic model as opposed to nearly €3.5 million without it. These findings are robust across all settings (described in Section 2) with the exception of setting 3 in which primary energy consumption must be reduced by 50% relative to the "do nothing" situation. While this is certainly possible, viz., by investing in larger DER systems, the higher expected discounted cost and risk exposure of 30% and 20%, respectively, may not be justifiable for the building owner. Further gains are possible with the use of thermal storage, whereas changes to the FiT (setting 2) or inclusion of a ToU tariff (setting 4) make little difference apart from rendering CHP units less attractive. Nevertheless, this example illustrates the capability of EnRiMa to provide managerial as well as policy insights.

Besides minimising expected costs, other objectives can also be considered. For example, Table 2 displays results with the minimisation of expected CO_2 emissions. We find that

Table 1: Summary of Results for FASAD: Expected Cost Minimisation Framework

	do nothing	invest	invest incl. storage	invest, setting 2	invest, setting 3	invest, setting 4
technology investment						
boiler (kW)						
CHP (kW)		11	11	5.5	27.5	5.5
PV (kW_p)		97.5	98	88.9	390	98
solar thermal (kW)		1,142.4	1,180.7	1,172.6	5,120.9	1,156.5
thermal storage (kWh)			100			
expected discounted cost						
cost (k€)	3,046	2,515	2,496	2,536	3,897	2,514
% savings		17.4%	18.1%	16.8%	-27.9%	17.5%
expected primary energy consumption						
energy consumed (MWh)	40,833	26,681	26,096	26,599	20,417	26,852
% savings		34.7%	36.1%	34.9%	50.0%	34.2%
expected CO_2 emissions						
emissions (ton)	7,473	4,893	4,785	4,875	3,748	4,921
% savings		34.5%	36.0%	34.8%	49.8%	34.1%
risk						
95% CVaR (k€)	3,467	2,824	2,797	2,833	4,145	2,813
% savings		18.5%	19.3%	18.3%	-19.6%	18.9%

the best way to achieve higher CO_2 emissions reductions is to adopt larger ST systems. However, relative to the case in Table 1, the expected incremental decrease in CO_2 emissions is only 2%, which may not be enough to offset the slightly higher expected discounted costs and risk. Finally, in Table 3, a risk-averse building owner's decision problem is solved by minimising the 95% CVaR of the discounted cost, i.e., the expected discounted cost given that the discounted cost is greater than the 95% value-at-risk (VaR). Although CVaR is slightly lowered as a result of investment, its gain comes at a relatively high discounted expected cost, i.e., €2.8 million, which is 10% higher than in the baseline "invest" setting of Table 1.

Table 2: Summary of Results for FASAD: Expected CO_2 Emissions Minimisation Framework

	do nothing	invest	invest incl. storage	invest, setting 2	invest, setting 3	invest, setting 4
technology investment						
boiler (kW)						
CHP (kW)		5.5	5.5		27.5	
PV (kW_p)		88.4	84.5	86.4	366	88.9
solar thermal (kW)		1,263.1	1,319.4	1,267.2	5,217.4	1,277.2
thermal storage (kWh)			100			
expected discounted cost						
cost (k€)	3,049	2,537	2,516	2,547	3,909	2,545
% savings		16.8%	17.5%	16.5%	-28.2%	16.5%
expected primary energy consumption						
energy consumed (MWh)	40,535	26,197	25,610	26,606	20,416	26,518
% savings		35.4%	36.8%	34.4%	49.6%	34.6%
expected CO_2 emissions						
emissions (ton)	7,419	4,801	4,693	4,872	3,748	4,856
% savings		35.3%	36.7%	34.3%	49.5%	34.6%
risk						
95% CVaR (k€)	3,049	2,826	2,804	2,845	4,157	2,840
% savings		7.3%	8.0%	6.7%	-36.4%	6.8%

Table 3: Summary of Results for FASAD: Risk Minimisation Framework

	do nothing	invest
technology investment		
boiler (kW)		
CHP (kW)		5.5
PV (kW_p)		95
solar thermal (kW)		1,237
thermal storage (kWh)		
expected discounted cost		
cost (k€)	3,059	2,776
% savings		9.2%
expected primary energy consumption		
energy consumed (MWh)	40,952	29,589
% savings		27.7%
expected CO_2 emissions		
emissions (ton)	7,493	5,422
% savings		27.6%
risk		
95% CVaR (k€)	3,467	2,822
% savings		18.6%

4.2 Pinkafeld

For Pinkafeld, the relatively low levels of CO_2 emissions from district heating and power mean that the building is in a good position from a sustainability perspective. In particular, compare the expected CO_2 emissions of 239 tons in Table 4 for the "do nothing" case with the corresponding one for FASAD in Table 1 (7473 tons). Nevertheless, as Tables 4–6 illustrate, improvements to the current configuration are still possible. For example, the installation of PV panels and ST collectors can reduce expected primary energy consumption and CO_2 emissions by 16% and 22%, respectively, along with modest reductions in expected cost and risk. As for FASAD, the imposition of requirements to reduce primary energy consumption (setting 3) results in an increase in expected costs. For Pinkafeld, the expected cost would soar to more than four times the current values because of already-high energy efficiency.

Table 4: Summary of Results for Pinkafeld: Expected Cost Minimisation Framework

	do nothing	invest	invest incl. storage	invest, setting 2	invest, setting 3	invest, setting 4
technology investment						
PV (kWp)		97.28	97.28	120.32	1800.96	96
solar thermal (kW)		4.48	38.73	4.48	100	4.48
thermal storage (kWh)			100			
expected discounted cost						
cost (k€)	929	888	872	863	4,423	867
% savings		4.5%	6.2%	7.1%	-375.9%	6.7%
expected primary energy consumption						
energy consumed (MWh)	12,008	10,096	9,107	9,822	8,406	10,115
% savings		15.9%	24.2%	18.2%	30.0%	15.8%
expected CO_2 emissions						
emissions (ton)	239	187	172	180	147	188
% savings		21.8%	28.0%	24.9%	38.6%	21.6%
risk						
95% CVaR (k€)	1,052	971	953	937	4,477	910
% savings		7.7%	9.5%	10.9%	-325.5%	13.5%

Elsewhere, the patterns of the results are broadly similar to those for FASAD: the availability of storage greatly enhances the expected primary energy savings, while offering a FiT for PV with a subsidy (setting 2) and switching to a ToU tariff (setting 4) modestly improve the metrics. Finally, using other objective functions, e.g., minimisation of expected CO_2 emissions or risk, implies that larger PV or ST systems are required at the expense of slightly higher expected discounted costs.

Table 5: Summary of Results for Pinkafeld: Expected CO_2 Emissions Minimisation Framework

	do nothing	invest	invest incl. storage	invest, setting 2	invest, setting 3	invest, setting 4
technology investment						
PV (kW$_p$)		89.6	88.32	108.8	1800.96	88.32
solar thermal (kW)		54.49	97.07	73.06	100	54.49
thermal storage (kWh)			100			
expected discounted cost						
cost (k€)	929	894	879	882	4,423	895
% savings		3.8%	5.4%	5.1%	-375.9%	3.7%
expected primary energy consumption						
energy consumed (MWh)	12,008	9,862	8,839	9,506	8,406	9,885
% savings		17.9%	26.4%	20.8%	30.0%	17.7%
expected CO_2 emissions						
emissions (ton)	239	185	170	176	147	186
% savings		22.6%	28.9%	26.3%	38.6%	22.3%
risk						
95% CVaR (k€)	1,052	978	963	959	4,477	943
% savings		7.0%	8.4%	8.9%	-325.5%	10.3%

Table 6: Summary of Results for Pinkafeld: Risk Minimisation Framework

	do nothing	invest
technology investment		
PV (kW$_p$)		108.8
solar thermal (kW)		10.81
thermal storage (kWh)		
expected discounted cost		
cost (k€)	930	895
% savings		3.8%
expected primary energy consumption		
energy consumed (MWh)	12,014	9,924
% savings		17.4%
expected CO_2 emissions		
emissions (ton)	239	183
% savings		23.5%
risk		
95% CVaR (k€)	1,036	968
% savings		6.6%

5 Conclusions

Current and forthcoming EU directives will require compliance with energy-efficiency measures. For example, after 2020, public buildings are supposed to become nearly zero energy. Thus, existing building owners face the challenge of deciding which technologies to adopt in the long term. Confounding their task are not only the manifold choices but also the uncertainty in energy prices and technology costs. Hence, addressing the building owner's attitude to risk is a crucial element of strategic decision support.

Given this background, we implement a stochastic model for analysing strategic decision making at the building level. Using two EU test sites, we calibrate parameters to be able to replicate their observed energy balances. Next, we generate scenarios for uncertain parameters over which we solve the resulting problem. We find that relative to the "do nothing" setting, the two sites are able to benefit from substantial savings in expected primary energy consumption, i.e., 35% at FASAD and 16% at Pinkafeld, with similar levels of expected CO_2 emissions reductions. These are accompanied by slightly lower improvements in economic and financial indicators. Finally, we are also able to investigate the effects of alternative regulatory settings and objective functions.

In this deliverable, we have met the requirements set forth in Task 7.5 of the DoW as follows:

1. Performed "what-if" analyses by providing guidance on equipment adoption given future uncertainties in prices, costs, and other parameters for various policies.

2. Examined how the proposed adoption would have performed given energy price and load data after calibration of the model to existing data.

3. Quantified and compared the tradeoffs from various policy measures and developed a framework for assessing the benefits of technology diffusion.

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Appendix A Strategic Model Formulation

In this appendix, we present the mathematical formulation of the strategic optimisation model.

A.1 Nomenclature

A.1.1 Sets

$\mathcal{A}$ Technology age, $a \in \mathcal{A}$. This set is used to model the effect of aging on the capacity and the costs of the technologies.

$\mathcal{I}$ Energy technology, $i \in \mathcal{I}$. Equipment available in the building, or suitable to be installed. This equipment can be: (1) energy generator, (2) energy storage, or (3) energy saver. Each element of the set is a specific model of a type of technology (e.g., CHP), with different features.

$\mathcal{K}$ Energy type, $k \in \mathcal{K}$. Type of energy that will be used in the building.

$\mathcal{L}$ Type of pollutant, $\ell \in \mathcal{L}$. Energy generation and consumption release pollutants into the environment. The amount of a building's emissions of each pollutant depends on the emission ratios. The total emissions can be constrained by policymakers. Their minimisation can also be an objective for certain decision makers.

$\mathcal{M}$ Operational profile, $m \in \mathcal{M}$. This set gathers the representative profiles considered in the model to link the short- and long-term performance of the energy systems in the building: the short-term performance is scaled to the long-term performance through a weight factor given as a parameter value.

$\mathcal{N}$ Energy tariff, $n \in \mathcal{N}$. This set contains the tariffs available throughout the planning horizon. It is possible that not all the tariffs are available at each scenario tree node.

$\mathcal{S}$ Scenario, $s \in \mathcal{S}$.

$\mathcal{T}$ Short-term (operational) period, $t \in \mathcal{T}$. These are the periods when operational decisions are made. Such decisions are concerned with how much energy of each type must flow through the building energy systems.

$\mathcal{V}$ Tree node, $v \in \mathcal{V}$. This set contains the nodes in the scenario tree. For each node, its time period, probability of occurrence, and parent node must be specified.

A.1.2 Subsets

$\mathcal{A}_{New} := \{0\}$, $\mathcal{A}_{New} \subset \mathcal{A}$. This set contains only the element 0 from the age set.

$\mathcal{A}_{Old} := \mathcal{A} \setminus \{0\}$, $\mathcal{A}_{Old} \subset \mathcal{A}$. This set contains all elements except 0 from the age set.

$\mathcal{I}_{Con}$ Continuously-sized technologies, $\mathcal{I}_{Con} \subset \mathcal{I}$. Technologies are continuously sized if they do not have a nominal capacity and the investment can be done by power units.

$\mathcal{I}_{Ds}$ Discretely-sized technologies, $\mathcal{I}_{Ds} \subset \mathcal{I}$. Technologies are discretely sized if they have a nominal capacity and the investment has to be done by devices.

$\mathcal{I}_{Gen}$ Energy-generation technologies, $\mathcal{I}_{Gen} \subset \mathcal{I}$. Technologies that receive energy as input and return other type(s) of energy as output.

$\mathcal{I}_{Inv}$ Technologies available for investment, $\mathcal{I}_{Inv} \subset \mathcal{I}$. Technologies that are available for investment and, hence, have an associated investment cost.

$\mathcal{I}_{PU}$ Passive technologies (unitary), $\mathcal{I}_{PU} \subset \mathcal{I}$. Passive technologies which have a multiplicative effect on the demand, that is, the higher the demand, the higher the savings. They provide savings over the use of energy regardless of the building dimensions.

$\mathcal{I}_{Sto}$ Storage technologies, $\mathcal{I}_{Sto} \subset \mathcal{I}$. Devices that store a given type of energy. These technologies are susceptible to energy losses during both charging and discharging as well as storage decay.

$\mathcal{K}_{Dem}$ Types of energy on the demand side, $\mathcal{K}_{Dem} \subset \mathcal{K}$.

$\mathcal{K}_{Epur}$ Types of energy which can be purchased, $\mathcal{K}_{Epur} \subset \mathcal{K}$.

$\mathcal{K}_{ES}$ Types of energy which can be sold, $\mathcal{K}_{ES} \subset \mathcal{K}$.

$\mathcal{N}_{Lim}$ Limited tariffs, $\mathcal{N}_{Lim} \subset \mathcal{N}$. Under limited tariffs, a maximum amount of energy can be traded.

$\mathcal{N}_{Tpur}$ Purchase tariffs, $\mathcal{N}_{Tpur} \subset \mathcal{N}$. This subset contains the tariffs available to buy energy.

$\mathcal{N}_{TS}$ Sales tariffs, $\mathcal{N}_{TS} \subset \mathcal{N}$. This subset contains the tariffs available to sell energy.

$\mathcal{V}_{Fut}$ Future nodes, $\mathcal{V}_{Fut} \subset \mathcal{V}$. All the nodes excluding the root node.

$\mathcal{V}_{Root}$ Root node, $\mathcal{V}_{Root} \subset \mathcal{V}$. This subset only contains the root node and is used to identify states at time 0, e.g., existing technologies.

A.1.3 Conditional sets

$\mathcal{A}^{i,v}_{Ages}$ Possible ages of a technology at a node, $i \in \mathcal{I}, v \in \mathcal{V}$.

$\mathcal{K}^{i}_{In}$ Input energy types for a technology, $i \in \mathcal{I}_{Gen}$. Generation technologies can utilise different types of energy to generate output energy.

$\mathcal{K}^{i}_{Out}$ Output energy types for a technology, $i \in \mathcal{I}_{Gen}$. Generation technologies provide one or more output energy types.

$\mathcal{K}^{i}_{Po}$ Principal energy of technologies, $i \in \mathcal{I}$. Each generation technology has a principal output type of energy (when having more than one output energy type). For storage technologies, the input and output types of energy are the same. For passive measures, it is the type of energy which is saved.

$Leaf(s)$ Leaf node of a scenario, $s \in \mathcal{S}$.

$\mathcal{N}^{k}_{Pur}$ Purchase tariffs for each energy type, $k \in \mathcal{K}_{Epur}$.

$\mathcal{N}^{k}_{Sal}$ Sales tariffs for each energy type, $k \in \mathcal{K}_{ES}$.

$\mathcal{N}^{k}_{Tr}$ Markets in which energy can be traded, $k \in \mathcal{K}$. This conditional set is the union of $\mathcal{N}^{k}_{Pur}$ and $\mathcal{N}^{k}_{Sal}$.

$Pa(v)$ Parent of a node, $v \in \mathcal{V}$.

$\mathcal{T}^{m}_{First}$ First short-term period in a profile, $m \in \mathcal{M}$.

$\mathcal{T}^{m}_{Last}$ Last short-term period in a profile, $m \in \mathcal{M}$.

$\mathcal{T}^{m}_{Tm}$ Short-term periods by profile, $m \in \mathcal{M}$. Each profile m can contain several operational periods, whose duration is modeled through the DM^m parameter.

$\mathcal{V}^{s}_{Path}$ Scenario path, $s \in \mathcal{S}$.

A.1.4 Constants

AL Confidence level for the CVaR.

BE Risk weight.

DR Annual discount rate.

A.1.5 Parameters

$AF_i^{v,m,t}$ Availability factor for a technology (kWh/kWh). $i \in \mathcal{I}$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}^m_{Tm}$. The capacity of a technology may be different throughout the optimisation horizon. For example, photovoltaic panels do not have the same performance during the day and cannot produce electric energy during the night. The availability factor can also be used to model the availability of future technologies.

AG_i^a Technology aging factor (kW/kWh). $i \in \mathcal{I}$, $a \in \mathcal{A}$. This parameter adjusts the total capacity of a technology throughout its lifetime. At age 0, a given technology has an aging factor of 1, and its capacity reduces at some rate each year.

$B_{k,n}$ Primary energy needed to produce final-use energy (kWh/kWh). $k \in \mathcal{K}_{Epur}$, $n \in \mathcal{N}^k_{Pur}$. Units of primary energy required to produce one unit of a type of energy available from a market where processed energy can be bought.

$CD_i^{v,a}$ Technology decommissioning cost (€/kW). $i \in \mathcal{I}$, $v \in \mathcal{V}$, $a \in \mathcal{A}$. Decommissioning a technology may lead to a removal cost or revenue from selling the equipment (in the latter case, the value of the parameter is negative).

CI_i^v Technology installation cost (€/kW). $i \in \mathcal{I}$, $v \in \mathcal{V}$.

CM_i^v Technology maintenance cost (€/kW, €/kWh). $i \in \mathcal{I}$, $v \in \mathcal{V}$. This is a fixed cost per installed capacity.

$CO_{i,k}^v$ Technology operation cost (€/kWh). $i \in \mathcal{I}_{Gen}$, $k \in \mathcal{K}^i_{Out}$, $v \in \mathcal{V}$.

$D_k^{v,m,t}$ Energy demand (kWh). $k \in \mathcal{K}_{Dem}$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}^m_{Tm}$. Total energy load of the building for a type of energy, during each short-term (operational) period.

DM^m Weight (scaling factor) for the operational profile in the objective (days). $m \in \mathcal{M}$. This parameter is used to scale the operational system performance (energy, cost) to the strategic time resolution.

DT^m Duration of the short-term period within a given profile (hours). $m \in \mathcal{M}$. The sum over the durations of all operational periods must correspond to a whole day. This parameter is used to convert energy to power or vice versa.

$EC^v_{i,k,k'}$ Output energy generated from one unit of input energy (kWh/kWh). $i \in \mathcal{I}_{Gen}$, $k \in \mathcal{K}^i_{In}$, $k' \in \mathcal{K}^i_{Out}$, $v \in \mathcal{V}$. This is a conversion factor. It is applied to the input energy of a technology to compute the output energy of this technology. Both types of energy can be the same or different. We may also have several types of output and input energy (e.g., natural gas, biogas).

EF^v Required building energy efficiency (unitless). $v \in \mathcal{V}$.

G_i Technology capacity (kW/Device). $i \in \mathcal{I}$. Nominal capacity of each device of a given technology. For continuous technologies, its value is 1.

IL^v Investment limit (€). $v \in \mathcal{V}$. This is needed when the building has a budget limit for investing in technologies.

$LC^v_{k,\ell,n}$ Pollution emissions by energy purchases (kg/kWh). $k \in \mathcal{K}$, $\ell \in \mathcal{L}$, $n \in \mathcal{N}^k_{Pur}$, $v \in \mathcal{V}$. Mean rate of emission of a pollutant from processed energy purchased in the market.

$LH^v_{k,\ell}$ Pollution emissions by generating technologies (kg/kWh). $k \in \mathcal{K}$, $\ell \in \mathcal{L}$, $v \in \mathcal{V}$. Amount of pollutant that is emitted by a generating technology during its operation, for each type of input energy.

LP^v_i Physical limit (Devices/kW/kWh). $i \in \mathcal{I}$, $v \in \mathcal{V}$. Number of units or capacity of a technology that can be installed at the site at a time.

$ME_{k,n}$ Maximum purchase/sale of a type of energy under a given contract (kW). $k \in \mathcal{K}$, $n \in \mathcal{N}^k_{Tr}$.

$OA^v_{i,k}$ Fraction of storage lower limit (kWh/kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}^i_{Po}$, $v \in \mathcal{V}$. Fraction of the storage capacity of an energy-storage technology below which the level of stored energy may not fall.

$OB^v_{i,k}$ Fraction of storage upper limit (kWh/kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}^i_{Po}$, $v \in \mathcal{V}$. Fraction of the storage capacity of an energy-storage technology which the level of stored energy may not exceed.

$OD^v_{i,k}$ Energy demand reduction for a passive technology (kWh/kWh). $i \in \mathcal{I}_{PU}$, $k \in \mathcal{K}^i_{Po}$, $v \in \mathcal{V}$. For each unit of a passive technology, the total demand is reduced by some value.

$OI^v_{i,k}$ Charging ratio to storage (kWh/kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}^i_{Po}$, $v \in \mathcal{V}$. Units of energy available for each unit charged into an energy-storage technology.

$OO^v_{i,k}$ Discharging ratio from storage (kWh/kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}^i_{Po}$, $v \in \mathcal{V}$. Units of energy needed to be discharged from storage in order to obtain one unit of energy.

$OS_{i,k}$ Energy storage availability (kWh/kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}^i_{Po}$. This parameter models the energy loss of a storage technology over time. It represents the amount of energy available after one short-time period per unit of energy stored.

$OX^v_{i,k}$ Max. discharge rate (kW/kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}^i_{Po}$, $v \in \mathcal{V}$. Maximum energy discharge rate per unit of storage capacity.

$OY^v_{i,k}$ Max. charge rate (kW/kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}^i_{Po}$, $v \in \mathcal{V}$. Maximum energy charge rate per unit of storage capacity.

PL^v_ℓ Pollution limit (kg). $\ell \in \mathcal{L}$, $v \in \mathcal{V}$. Pollution limit for the building for each year.

$PP^{v,m,t}_{k,n}$ Energy purchasing cost (€/kWh). $k \in \mathcal{K}$, $n \in \mathcal{N}^k_{Pur}$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}^m_{Tm}$. Cost of energy in markets where it can be bought.

PR^v Probability of the node (unitless). $v \in \mathcal{V}$.

PT^v Time period of the node (unitless). $v \in \mathcal{V}$.

$SP_{k,n}^{v,m,t}$ Energy sales price (€/kWh). $k \in \mathcal{K}$, $n \in \mathcal{N}_{Sal}^k$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^m$. For the types of energy that can be sold, there is a price for each operational period.

SU_i^v Subsidies for a technology (€/kW). $i \in \mathcal{I}$, $v \in \mathcal{V}$. Policy makers can subsidise the investment of some efficient technologies. Usually an amount per kW is paid.

XZ_i^a Existing devices (Devices/kW/kWh). $i \in \mathcal{I}$, $a \in \mathcal{A}$. Number of existing devices of each technology of a given age at the start of the optimisation horizon.

A.1.6 Decision Variables

c Total expected discounted cost (€).

cn^v Total discounted cost at a node (€). $v \in \mathcal{V}$.

dn_k^v Total demand at a node (kWh). $k \in \mathcal{K}$, $v \in \mathcal{V}$.

$e^{v,m,t}$ Primary energy consumed per operational period (kWh). $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^m$. This is a computed variable for the energy consumption of the building during each short-term period.

en^v Total energy consumed at a node (kWh). $v \in \mathcal{V}$.

ep^v Energy consumed and sold (kWh). $v \in \mathcal{V}$.

et Total averaged energy consumed (kWh).

$h_{k,n}^v$ Tariff choice (binary). $k \in \mathcal{K}$, $n \in \mathcal{N}_{Tr}^k$, $v \in \mathcal{V}$. Decision variable for selecting among different tariffs. The choice is done for the subsequent period.

mn_i^v Fixed (maintenance) cost at a node (€). $i \in \mathcal{I}$, $v \in \mathcal{V}$.

oc Weighted average of the mean and risk of the total discounted cost (€).

oe Weighted average of the mean and risk of the primary energy consumed (kWh).

op Weighted average of the mean and risk of the pollution emissions (kg).

p Total averaged pollution emissions (kg).

pn_ℓ^v Total emissions at a node (kg). $\ell \in \mathcal{L}$, $v \in \mathcal{V}$.

$r_{i,k}^{v,m,t}$ Energy stored (kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}_{Po}^i$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^m$. The amount of energy that is stored in a given energy-storage technology at the start of a given short-term period.

$ra_{i,k}^v$ Sum of energy stored at the beginning of short-term periods (kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}_{Po}^i$, $v \in \mathcal{V}$.

$rc_{i,k}^v$ Total storage operational cost at a node (kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}_{Po}^i$, $v \in \mathcal{V}$.

$ri_{i,k}^{v,m,t}$ Energy input to storage (kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}_{Po}^i$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^m$. Amount of energy charged into a given energy-storage technology during a given short-term period.

$rn_{i,k}^v$ Total energy input to storage at a node (kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}_{Po}^i$, $v \in \mathcal{V}$.

$ro_{i,k}^{v,m,t}$ Energy output from storage (kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}_{Po}^i$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^m$. Amount of energy discharged from a given energy-storage technology during a given short-term period.

$rp_{i,k}^{v}$ Total energy output from storage at a node (kWh). $i \in \mathcal{I}_{Sto}$, $k \in \mathcal{K}_{Po}^{i}$, $v \in \mathcal{V}$.

rt Risk term (CVaR) (€/kg/kWh). Average cost/primary energy consumed/pollution emissions of $(1 - AL) \times 100\%$ worst scenarios.

sd_{i}^{v} Decommissioning cost at a node per technology (€/kW). $i \in \mathcal{I}$, $v \in \mathcal{V}$.

sn_{i}^{v} Strategic (investment) installation cost at a node for a technology (€). $i \in \mathcal{I}$, $v \in \mathcal{V}$.

sr^{s} Auxiliary variable to calculate CVaR (€/kg/kWh). $s \in \mathcal{S}$.

$u_{k,n}^{v,m,t}$ Energy to purchase under a given tariff (kWh). $k \in \mathcal{K}_{Epur}$, $n \in \mathcal{N}_{Pur}^{k}$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^{m}$. Amount of energy purchased in the market, to be delivered during each operational period.

$uc_{k,n}^{v}$ Total energy purchasing costs at a node for each energy type and contract (€). $k \in \mathcal{K}_{Epur}$, $n \in \mathcal{N}_{Pur}^{k}$, $v \in \mathcal{V}$.

$un_{k,n}^{v}$ Total energy purchases at a node for each energy type and contract (kWh). $k \in \mathcal{K}_{Epur}$, $n \in \mathcal{N}_{Pur}^{k}$, $v \in \mathcal{V}$.

vr VaR at confidence level AL (€/kg/kWh). The lowest cost that ensures that the probability that the loss exceeds this value is at most $(1 - AL)$.

$w_{k,n}^{v,m,t}$ Energy to sell under a given tariff (kWh). $k \in \mathcal{K}_{ES}$, $n \in \mathcal{N}_{Sal}^{k}$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^{m}$. Amount of energy to be sold in the market during a given operational period.

$wc_{k,n}^{v}$ Total energy sales revenue at a node for each energy type and contract (€). $k \in \mathcal{K}_{ES}$, $n \in \mathcal{N}_{Sal}^{k}$, $v \in \mathcal{V}$.

$wn_{k,n}^{v}$ Total energy sales at a node for each energy type and contract (kWh). $k \in \mathcal{K}_{ES}$, $n \in \mathcal{N}_{Sal}^{k}$, $v \in \mathcal{V}$.

$x_i^{v,a}$ Installed units of a given age for each technology and node (Devices/kW/kWh). $i \in \mathcal{I}$, $v \in \mathcal{V}$, $a \in \mathcal{A}_{Ages}^{i,v}$.

xc_i^v Available capacity of a technology at each node (kW or kWh (storage)). $i \in \mathcal{I}$, $v \in \mathcal{V}$.

$xd_i^{v,a}$ Number of units of a technology to be decommissioned (Devices or kW). Integer for $i \in \mathcal{I}_{Ds}$, $v \in \mathcal{V}$, $a \in \mathcal{A}_{Old} \cap \mathcal{A}_{Ages}^{i,v}$; continuous for $i \in \mathcal{I}_{Con}$, $v \in \mathcal{V}$, $a \in \mathcal{A}_{Old} \cap \mathcal{A}_{Ages}^{i,v}$. For continuously-sized technologies, this is the total capacity to be decommissioned. For discretely-sized technologies, it denotes the number of devices to decommission.

xi_i^v Number of units of a technology to be installed (Devices or kW). Integer for $i \in \mathcal{I}_{Ds}$, $v \in \mathcal{V}$; continuous for $i \in \mathcal{I}_{Con}$, $v \in \mathcal{V}$. For discretely-sized technologies, this is an integer variable, whilst for continuously-sized technologies, it is a continuous one.

$y_{i,k}^{v,m,t}$ Energy generator input (kWh). $i \in \mathcal{I}_{Gen}$, $k \in \mathcal{K}_{In}^i$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^m$. Amount of energy used as input to an energy-creating technology, for each type of energy, operational profile and period.

$yn_{i,k}^v$ Total energy input at a node for each technology and type of energy (kWh). $i \in \mathcal{I}_{Gen}$, $k \in \mathcal{K}_{In}^i$, $v \in \mathcal{V}$.

$z_{i,k}^{v,m,t}$ Energy generator output (kWh). $i \in \mathcal{I}_{Gen}$, $k \in \mathcal{K}_{Out}^i$, $v \in \mathcal{V}$, $m \in \mathcal{M}$, $t \in \mathcal{T}_{Tm}^m$. Amount of energy generated by an energy-creating technology for each type of energy, operational profile and short-term period.

$zc_{i,k}^v$ Total energy generation (operation) costs at a node for each technology and principal output energy type (€). $i \in \mathcal{I}_{Gen}$, $k \in \mathcal{K}_{Out}^i$, $v \in \mathcal{V}$.

$zn_{i,k}^v$ Total energy generated at a node for each technology and energy type (kWh). $i \in \mathcal{I}_{Gen}$, $k \in \mathcal{K}_{Out}^i$, $v \in \mathcal{V}$.

A.2 Strategic Model

A.2.1 Strategic Constraints

Available new technologies (devices) at each node

The number of available new devices (i.e., whose age is zero) of a technology is equal to the number of devices installed at each node:

$$x_i^{v,a} = xi_i^v \quad \forall\, v \in \mathcal{V},\;\; a \in \mathcal{A}_{New},\; i \in \mathcal{I}_{Inv}. \tag{1}$$

Available old technologies (devices) at future nodes

The number of available devices whose age is not zero is equal to the number of available devices at the preceding node less the number of decommissioned devices:

$$x_i^{v,a} = x_i^{Pa(v),a-1} - xd_i^{v,a} \quad \forall\, i \in \mathcal{I},\;\; a \in \mathcal{A}_{Old} \cap \mathcal{A}_{Ages}^{i,v}, v \in \mathcal{V}_{Fut}. \tag{2}$$

Available old technologies (devices) at root node

The number of devices available at the root node is equal to the number of existing devices at the start of the optimisation horizon minus the number of devices decommissioned at the root node:

$$x_i^{v,a} = XZ_i^a - xd_i^{v,a} \quad \forall\, i \in \mathcal{I},\;\; a \in \mathcal{A}_{Old} \cap \mathcal{A}_{Ages}^{i,v}, v \in \mathcal{V}_{Root}. \tag{3}$$

Technology capacity calculation

The total capacity of a technology is equal to the sum of the number of installed devices, corrected by their respective aging factor and nominal capacity:

$$xc_i^v = G_i \cdot \sum_{a \in \mathcal{A}_{Ages}^{i,v}} AG_i^a \cdot x_i^{v,a} \quad \forall\, i \in \mathcal{I},\; v \in \mathcal{V}. \tag{4}$$

Investment limit

An upper limit may be imposed on the total installation and decommissioning cost at each node:

$$\sum_{i \in \mathcal{I}_{Inv}} sn_i^v + \sum_{i \in \mathcal{I}} sd_i^v \leq IL^v \quad \forall\, v \in \mathcal{V}. \tag{5}$$

Purchasing tariff choice

Only one purchasing tariff is allowed per node:

$$\sum_{n \in \mathcal{N}_{Pur}^{k}} h_{k,n}^{v} = 1 \quad \forall\, v \in \mathcal{V}, \;\; k \in \mathcal{K}_{Epur}. \tag{6}$$

Sales tariff choice

Only one sales tariff is allowed per node:

$$\sum_{n \in \mathcal{N}_{Sal}^{k}} h_{k,n}^{v} = 1 \quad \forall\, v \in \mathcal{V}, \;\; k \in \mathcal{K}_{ES}. \tag{7}$$

Physical limit

Typically, there is a limit for installing technologies, which usually depends on the space available at the site. Note that within the optimiser, it can be implemented as a variable upper limit rather than a constraint:

$$\sum_{a \in \mathcal{A}_{Ages}^{i,v}} x_{i}^{v,a} \leq LP_{i}^{v} \quad \forall\, i \in \mathcal{I}, \; v \in \mathcal{V}. \tag{8}$$

Emissions limit

The total emissions of a given pollutant may not exceed a specified limit:

$$pn_{\ell}^{v} \leq PL_{\ell}^{v} \quad \forall\, \ell \in \mathcal{L}, \; v \in \mathcal{V}. \tag{9}$$

A.2.2 Operational Constraints

Storage available

The energy available in storage at the start of a given short-term period is equal to the energy stored at the start of the previous short-term period plus the energy sent to storage minus the energy removed from storage during this period. Each type of energy flow is corrected by its respective loss ratio parameter:

$$r_{i,k}^{v,m,t+1} = OS_{i,k} \cdot r_{i,k}^{v,m,t} + OI_{i,k}^{v} \cdot ri_{i,k}^{v,m,t} - OO_{i,k}^{v} \cdot ro_{i,k}^{v,m,t} \tag{10}$$
$$\forall\, v \in \mathcal{V}, \; m \in \mathcal{M}, \;\; i \in \mathcal{I}_{Sto}, \; t \in \mathcal{T}_{Tm}^{m}, k \in \mathcal{K}_{Po}^{i}.$$

Storage level between periods

The storage level at the start of the first short-term period must be equal to the storage level at the end of the last short-term period in the same operational profile and node:

$$r_{i,k}^{v,m,t} = OS_{i,k} \cdot r_{i,k}^{v,m,t'} + OI_{i,k}^{v} \cdot ri_{i,k}^{v,m,t'} - OO_{i,k}^{v} \cdot ro_{i,k}^{v,m,t'} \tag{11}$$
$$\forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ i \in \mathcal{I}_{Sto},\ k \in \mathcal{K}_{Po}^{i}, t \in \mathcal{T}_{First}^{m}, t' \in \mathcal{T}_{Last}^{m}.$$

Energy balance

For each energy type, the net energy supply must meet the net energy demand in each time period. The latter consists of the energy demand less the energy saved due to passive technologies, whereas the former consists of the energy produced by energy-creating technologies plus the energy discharged from storage and the energy purchases in the energy market less the energy used for production or charging storage devices and the energy sold:

$$\sum_{i \in \mathcal{I}_{Gen}} z_{i,k}^{v,m,t} - \sum_{i \in \mathcal{I}_{Gen}} y_{i,k}^{v,m,t} + \sum_{n \in \mathcal{N}_{Pur}^{k}} u_{k,n}^{v,m,t} - \sum_{n \in \mathcal{N}_{Sal}^{k}} w_{k,n}^{v,m,t} \tag{12}$$
$$+ \sum_{i \in \mathcal{I}_{Sto}} \left(ro_{i,k}^{v,m,t} - ri_{i,k}^{v,m,t} \right) = D_{k}^{v,m,t} \cdot \left(1 - \sum_{i \in \mathcal{I}_{PU}} OD_{i,k}^{v} \cdot xc_{i}^{v} \right)$$
$$\forall\, k \in \mathcal{K},\ v \in \mathcal{V},\ m \in \mathcal{M},\ t \in \mathcal{T}_{Tm}^{m}.$$

Sales limit by generation capacity

The amount of energy to be sold cannot exceed the amount of energy produced on site:

$$\sum_{n \in \mathcal{N}_{Sal}^{k}} w_{k,n}^{v,m,t} \le \sum_{i \in \mathcal{I}_{Gen}} z_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ k \in \mathcal{K}_{ES},\ t \in \mathcal{T}_{Tm}^{m}. \tag{13}$$

A.2.3 Strategic-Operational Link Constraints

Technology output limit

The amount of energy that can be produced by a technology is constrained by the technology's availability and capacity:

$$z_{i,k}^{v,m,t} \le DT^{m} \cdot AF_{i}^{v,m,t} \cdot xc_{i}^{v} \quad \forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ i \in \mathcal{I}_{Gen},\ k \in \mathcal{K}_{Po}^{i}, t \in \mathcal{T}_{Tm}^{m}. \tag{14}$$

Storage discharge limit

The amount of energy that can be discharged from any energy-storage technology is limited by the technology's installed capacity and maximum discharge rate:

$$ro_{i,k}^{v,m,t} \le OX_{i,k}^{v} \cdot DT^{m} \cdot xc_{i}^{v} \quad \forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ i \in \mathcal{I}_{Sto},\ t \in \mathcal{T}_{Tm}^{m}, k \in \mathcal{K}_{Po}^{i}. \tag{15}$$

Storage charge limit

The amount of energy that can be charged to a given energy-storage technology is limited by the technology's installed capacity and maximum charge rate:

$$ri_{i,k}^{v,m,t} \leq OY_{i,k}^{v} \cdot DT^{m} \cdot xc_{i}^{v} \quad \forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ i \in \mathcal{I}_{Sto},\ t \in \mathcal{T}_{Tm}^{m}, k \in \mathcal{K}_{Po}^{i}. \tag{16}$$

Lower storage limit

The amount of energy that can be stored in any energy-storage technology must be greater than the capacity installed corrected by the respective minimum charge ratio:

$$r_{i,k}^{v,m,t} \geq OA_{i,k}^{v} \cdot xc_{i}^{v} \quad \forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ i \in \mathcal{I}_{Sto},\ t \in \mathcal{T}_{Tm}^{m}, k \in \mathcal{K}_{Po}^{i}. \tag{17}$$

Upper storage limit

The amount of energy that can be stored in any energy-storage technology must be lower than the capacity installed corrected by the respective maximum charge ratio:

$$r_{i,k}^{v,m,t} \leq OB_{i,k}^{v} \cdot xc_{i}^{v} \quad \forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ i \in \mathcal{I}_{Sto},\ t \in \mathcal{T}_{Tm}^{m}, k \in \mathcal{K}_{Po}^{i}. \tag{18}$$

Purchasing limit by contract

The amount of energy that can be purchased at a given node must not exceed the amount stipulated in the signed purchase contract:

$$u_{k,n}^{v,m,t} \leq h_{k,n}^{v} \cdot ME_{k,n} \cdot DT^{m} \tag{19}$$
$$\forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ k \in \mathcal{K}_{Epur},\ n \in \mathcal{N}_{Lim} \cap \mathcal{N}_{Pur}^{k}, t \in \mathcal{T}_{Tm}^{m}.$$

Sales limit by contract

The amount of energy that can be sold at a given node must not exceed the amount agreed in the signed sales contract:

$$w_{k,n}^{v,m,t} \leq h_{k,n}^{v} \cdot ME_{k,n} \cdot DT^{m} \tag{20}$$
$$\forall\, v \in \mathcal{V},\ m \in \mathcal{M},\ \ k \in \mathcal{K}_{ES},\ n \in \mathcal{N}_{Lim} \cap \mathcal{N}_{Sal}^{k}, t \in \mathcal{T}_{Tm}^{m}.$$

Required efficiency

The amount of energy consumed and sold must be larger than the amount of primary energy consumed corrected by the efficiency parameter:

$$ep^{v} \geq EF^{v} \cdot en^{v} \quad \forall\, v \in \mathcal{V}. \tag{21}$$

A.2.4 Computation Constraints

Installation cost of a technology

The net installation cost of a given technology is equal to the technology's installation cost less subsidies.

$$sn_i^v = (CI_i^v - SU_i^v) \cdot G_i \cdot xi_i^v \quad \forall\, v \in \mathcal{V},\;\; i \in \mathcal{I}_{Inv}. \tag{22}$$

Decommissioning cost of a technology

The decommissioning cost of a technology depends on the age and capacity of the devices to be decommissioned:

$$sd_i^v = \sum_{a \in \mathcal{A}_{Ages}^{i,v}} CD_i^{v,a} \cdot G_i \cdot xd_i^{v,a} \quad \forall\, i \in \mathcal{I},\; v \in \mathcal{V}. \tag{23}$$

Output energy production

The amount of output energy produced by an energy-generating technology is calculated from the input energy and the technology's energy-conversion factor:

$$z_{i,k'}^{v,m,t} = \sum_{k \in \mathcal{K}_{In}^i} EC_{i,k,k'}^v \cdot y_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\; m \in \mathcal{M},\;\; i \in \mathcal{I}_{Gen},\; k' \in \mathcal{K}_{Out}^i, t \in \mathcal{T}_{Tm}^m. \tag{24}$$

Primary energy consumption

The primary energy consumed is equal to the sum of the amount of energy purchased of each type adjusted by the respective off-site energy-conversion factor.

$$e^{v,m,t} = \sum_{\mathcal{K}_{Epur}, n \in \mathcal{N}_{Pur}^k} B_{k,n} \cdot u_{k,n}^{v,m,t} \quad \forall\, v \in \mathcal{V},\; m \in \mathcal{M},\; t \in \mathcal{T}_{Tm}^m. \tag{25}$$

Total cost

The total cost is composed of the net investment, decommissioning, maintenance, energy trading, and technology operation costs.

$$\begin{aligned} cn^v = \sum_{i \in \mathcal{I}_{Inv}} sn_i^v + \sum_{i \in \mathcal{I}} sd_i^v + \sum_{i \in \mathcal{I}} mn_i^v \\ + \sum_{k \in \mathcal{K}_{Epur}, n \in \mathcal{N}_{Pur}^k} uc_{k,n}^v - \sum_{k \in \mathcal{K}_{ES}, n \in \mathcal{N}_{Sal}^k} wc_{k,n}^v \\ + \sum_{i \in \mathcal{I}_{Gen}} zc_{i,k}^v + \sum_{i \in \mathcal{I}_{Sto}} rc_{i,k}^v \quad \forall\, v \in \mathcal{V}. \end{aligned} \tag{26}$$

Total discounted expected cost

$$c = \sum_{v \in \mathcal{V}} (1 + DR)^{-PT^v} \cdot PR^v \cdot cn^v. \tag{27}$$

Total primary energy consumption

$$en^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{t \in \mathcal{T}_{Tm}^m} e^{v,m,t} \quad \forall\, v \in \mathcal{V}. \tag{28}$$

Total average primary energy consumption

$$et = \sum_{v \in \mathcal{V}} PR^v \cdot en^v. \tag{29}$$

Energy consumed and sold

$$ep^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{k \in \mathcal{K}, t \in \mathcal{T}_{Tm}^m} \left(D_k^{v,m,t} + \sum_{n \in \mathcal{N}_{Sal}^k} w_{k,n}^{v,m,t} \right) \quad \forall\, v \in \mathcal{V}. \tag{30}$$

Total emissions of a pollutant

The total pollution emissions consist of the pollution emissions by energy purchases and energy-generating technologies.

$$pn_\ell^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{t \in \mathcal{T}_{Tm}^m} \left(\sum_{i \in \mathcal{I}_{Gen}, k \in \mathcal{K}_{In}^i} LH_{k,\ell}^v \cdot y_{i,k}^{v,m,t} + \sum_{k \in \mathcal{K}_{Epur}, n \in \mathcal{N}_{Pur}^k} LC_{k,\ell,n}^v \cdot u_{k,n}^{v,m,t} \right) \tag{31}$$

$$\forall\, \ell \in \mathcal{L},\; v \in \mathcal{V}.$$

Total average emissions

$$p = \sum_{v \in \mathcal{V}} PR^v \cdot \sum_{\ell \in \mathcal{L}} pn_\ell^v. \tag{32}$$

A.2.5 Aggregation Constraints

Aggregated maintenance cost

$$mn_i^v = CM_i^v \cdot G_i \cdot \sum_{a \in \mathcal{A}_{Ages}^{i,v}} x_i^{v,a} \quad \forall\, i \in \mathcal{I},\ v \in \mathcal{V}. \tag{33}$$

Aggregated energy purchases

$$un_{k,n}^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{t \in \mathcal{T}_{Tm}^m} u_{k,n}^{v,m,t} \quad \forall\, k \in \mathcal{K}_{Epur},\ v \in \mathcal{V},\ n \in \mathcal{N}_{Pur}^k. \tag{34}$$

Aggregated energy purchases cost

$$uc_{k,n}^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{t \in \mathcal{T}_{Tm}^m} PP_{k,n}^{v,m,t} \cdot u_{k,n}^{v,m,t} \quad \forall\, k \in \mathcal{K}_{Epur},\ v \in \mathcal{V},\ n \in \mathcal{N}_{Pur}^k. \tag{35}$$

Aggregated energy sales for each type of energy

$$wn_{k,n}^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{t \in \mathcal{T}_{Tm}^m} w_{k,n}^{v,m,t} \quad \forall\, k \in \mathcal{K}_{ES},\ v \in \mathcal{V},\ n \in \mathcal{N}_{Sal}^k. \tag{36}$$

Aggregated energy sales revenue

$$wc_{k,n}^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{t \in \mathcal{T}_{Tm}^m} SP_{k,n}^{v,m,t} \cdot w_{k,n}^{v,m,t} \quad \forall\, k \in \mathcal{K}_{ES},\ v \in \mathcal{V},\ n \in \mathcal{N}_{Sal}^k. \tag{37}$$

Aggregated energy generated

$$zn_{i,k}^v = \sum_{m \in \mathcal{M}} DM^m \cdot \sum_{t \in \mathcal{T}_{Tm}^m} z_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\ \ i \in \mathcal{I}_{Gen},\ k \in \mathcal{K}_{Out}^i. \tag{38}$$

Aggregated energy generation cost

$$zc_{i,k}^{v} = \sum_{m\in\mathcal{M}} DM^{m} \cdot \sum_{t\in\mathcal{T}_{Tm}^{m}} CO_{i,k}^{v} \cdot z_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\;\; i \in \mathcal{I}_{Gen},\; k \in \mathcal{K}_{Po}^{i}. \tag{39}$$

Aggregated energy storage cost

$$rc_{i,k}^{v} = \sum_{m\in\mathcal{M}} DM^{m} \cdot \sum_{t\in\mathcal{T}_{Tm}^{m}} CO_{i,k}^{v} \cdot ro_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\;\; i \in \mathcal{I}_{Sto},\; k \in \mathcal{K}_{Po}^{i}. \tag{40}$$

Aggregated input energy to each technology

$$yn_{i,k}^{v} = \sum_{m\in\mathcal{M}} DM^{m} \cdot \sum_{t\in\mathcal{T}_{Tm}^{m}} y_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\;\; i \in \mathcal{I}_{Gen},\; k \in \mathcal{K}_{In}^{i}. \tag{41}$$

Aggregated energy stored

$$ra_{i,k}^{v} = \sum_{m\in\mathcal{M}} DM^{m} \cdot \sum_{t\in\mathcal{T}_{Tm}^{m}} r_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\;\; i \in \mathcal{I}_{Sto},\; k \in \mathcal{K}_{Po}^{i}. \tag{42}$$

Aggregated energy input to storage

$$rn_{i,k}^{v} = \sum_{m\in\mathcal{M}} DM^{m} \cdot \sum_{t\in\mathcal{T}_{Tm}^{m}} ri_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\;\; i \in \mathcal{I}_{Sto},\; k \in \mathcal{K}_{Po}^{i}. \tag{43}$$

Aggregated energy output from storage

$$rp_{i,k}^{v} = \sum_{m\in\mathcal{M}} DM^{m} \cdot \sum_{t\in\mathcal{T}_{Tm}^{m}} ro_{i,k}^{v,m,t} \quad \forall\, v \in \mathcal{V},\;\; i \in \mathcal{I}_{Sto},\; k \in \mathcal{K}_{Po}^{i}. \tag{44}$$

Total nodal demand

$$dn_{k}^{v} = \sum_{m\in\mathcal{M}} DM^{m} \cdot \sum_{t\in\mathcal{T}_{Tm}^{m}} D_{k}^{v,m,t} \quad \forall\, k \in \mathcal{K},\; v \in \mathcal{V}. \tag{45}$$

A.2.6 Risk Constraints

Risk term calculation

Eq. (46) calculates the CVaR at a confidence level of $AL \times 100\%$, that is, the expected value of the selected metric in the worst $(1 - AL) \times 100\%$ cases.

$$rt = vr + (1 - AL)^{-1} \cdot \sum_{s \in \mathcal{S}} PR^{Leaf(s)} \cdot sr^s. \tag{46}$$

Risk constraints for cost minimisation

Eq. (47) is necessary for calculating the CVaR of the total discounted costs.

$$\sum_{v \in \mathcal{V}^s_{Path}} (1 + DR)^{-PT^v} \cdot cn^v - vr \leq sr^s \quad \forall\, s \in \mathcal{S}. \tag{47}$$

Risk constraints for emissions minimisation

Eq. (48) is necessary for calculating the CVaR of the total pollution emissions.

$$\sum_{\ell \in \mathcal{L}, v \in \mathcal{V}^s_{Path}} pn^v_\ell - vr \leq sr^s \quad \forall\, s \in \mathcal{S}. \tag{48}$$

Risk constraints for consumed energy minimisation

Eq. (49) is necessary for calculating the CVaR of the overall primary energy consumption.

$$\sum_{v \in \mathcal{V}^s_{Path}} en^v - vr \leq sr^s \quad \forall\, s \in \mathcal{S}. \tag{49}$$

A.2.7 Mean-Risk Constraints

Weighted cost and risk objective

Eq. (50) calculates a weighted average of the expected value and CVaR of the total discounted costs.

$$oc = (1 - BE) \cdot c + BE \cdot rt. \tag{50}$$

Weighted emissions and risk objective

Eq. (51) calculates a weighted average of the expected value and CVaR of the overall pollution emissions.

$$op = (1 - BE) \cdot p + BE \cdot rt. \tag{51}$$

Weighted energy and risk objective

Eq. (52) computes a weighted average of the expected value and CVaR of the overall primary energy consumption.

$$oe = (1 - BE) \cdot et + BE \cdot rt. \tag{52}$$

A.2.8 Objective Function

In our strategic optimisation model, we consider a mean-risk objective function of either the total discounted cost, the total pollution emissions, or the total primary energy consumed. The risk and mean-risk constraints of the metrics that are not comprised in the objective function are excluded from the optimisation model. For instance, if the total discounted cost is selected, then the goal is to

$$\text{Minimise} \quad oc \tag{53}$$

subject to constraints (1)–(47) and (50). Thus, the risk and mean-risk constraints involving pollution emissions and primary energy consumption are excluded from the model in this setting.

Appendix B Input Parameters of Numerical Examples

In this appendix, we describe the input parameters used in Section 4. Unless otherwise indicated, these are valid for every regulatory setting of a given site; see Section 2 for a description of the regulatory settings. The input parameters are calibrated in order to yield the same energy balances as those observed for the test buildings in the current year, cf. Deliverables D1.1 (HCE et al., 2011) and D2.2 (UCL et al., 2012). For FASAD, the parameter values for new equipment were collected from energy-industry catalogues, whereas the values reported in Groissböck et al. (2011) were used for Pinkafeld.

B.1 FASAD

Table 7: Energy-Generation Technology Parameters for FASAD

i	K_{In}	K_{Out}	CI^0 (€/kW)	CM (€/kW)	EC	G (kW)	LH (kg/kWh)
boiler 1	natural gas	heat	9.3167	0	0.925	1279.1	0.1836
boiler 2	natural gas	heat	14.1359	0	0.92	232.6	0.1836
boiler 3	natural gas	heat	27.2172	0	0.93	290.0	0.1836
CHP	natural gas	electricity	5255.4550	0	0.2683	5.5	0.1836
		heat			0.6098		
PV	solar radiation	electricity	1371.4286	0	0.1461	0.245	0
ST	solar radiation	heat	341.0645	0	0.795	2.011	0

Table 8: Thermal Storage Parameters for FASAD

parameter	value
CI^0 (€/kWh)	100.0
OA	0.00
OB	1.00
OI	0.90
OO	1.00
OS	0.99
OX (kW/kWh)	0.25
OY (kW/kWh)	0.25

Table 9: Energy Tariff Parameters for FASAD

k	n	type	B	LC (kg/kWh)	ME (kW)	PP^0 (€/kWh)	SP^0 (€/kWh)
electricity	flat tariff	purchase	2.0624	0.37	100.0	0.14263	
electricity	feed-in tariff	sale			5.5		0.17215
natural gas	flat tariff	purchase	1.0	0.0	1426.3	0.05227	
solar radiation		purchase	0	0		0	

Table 10: Annual Growth Rate of FASAD's Random Parameters

parameter	mean	volatility
electricity prices	7.6%	4.3%
installation costs	0.0%	1.0%
natural gas prices	9.6%	6.9%

B.2 Pinkafeld

Table 11: Energy-Generation Technology Parameters for Pinkafeld

i	K_{In}	K_{Out}	CI^0 (€/kW)	CM (€/kW)	EC	G (kW)	LH (kg/kWh)
HVAC	electricity	cooling	1000.0	0.0139	3.5	79.80	0
PV	solar radiation	electricity	2331.1	0.1740	0.125	1.28	0
ST	solar radiation	heat	358.0	0.107	0.5	1.00	0

Table 12: Thermal Storage Parameters for Pinkafeld

parameter	value
CI^0 (€/kWh)	71.62
OA	0.00
OB	1.00
OI	0.90
OO	1.00
OS	0.99
OX (kW/kWh)	0.25
OY (kW/kWh)	0.25

Table 13: Energy Tariff Parameters for Pinkafeld

k	n	type	B	LC (kg/kWh)	ME (kW)	PP^0 (€/kWh)	SP^0 (€/kWh)
district heating	flat tariff	purchase	2.0	0.03	120.0	0.08028	
electricity	flat tariff	purchase	1.089	0.03	100.0	0.15	
electricity	flat tariff	sale			100.0		0.0759
solar radiation		purchase	0	0		0	

Table 14: Annual Growth Rate of Pinkafeld's Random Parameters

parameter	mean	volatility
district heating prices	3.4%	6.1%
electricity prices	5.3%	7.8%
installation costs	0.0%	1.0%

Appendix C Epidemic Model for Technology Diffusion

In order for the EnRiMa strategic DSS to become commercially viable, preliminary market analysis is required. Using the results of our strategic model, an epidemic model for technology diffusion applied to DER in the U.S. (Maribu et al., 2007), and supplementary data on available floor space for DSS adoption in EU15 countries (Petersdorff et al., 2005), we forecast patterns for successful DSS adoption for EU15 countries from the project's end to 2025.

Based on Maribu et al. (2007), the incremental building floor space adopting the DSS each year depends on three factors:

1. Propagation of knowledge;
2. Propensity for adoption as a function of economic benefits;
3. Residual floor space suitable for adoption.

Thus, mathematically, we have the following expressions that forecast DSS adoption:

$$A_m = (\alpha + \beta X_{m-1})\, f_m(s_m)\, (T_m - D_m) \tag{54}$$

$$f_m(s_m) = \frac{c}{(1 + ae^{-bs_m})} - \frac{c}{(1+a)} \tag{55}$$

$$D_m = D_{m-1} + A_m \tag{56}$$

$$X_m = \frac{D_m}{T_m} \tag{57}$$

Here, A_m (in m^2) is the floor space that adopts the DSS in year m, T_m (in m^2) is the total available floor space for DSS adoption in year m, D_m (in m^2) is the cumulative floor space with DSS in year m, s_m is the percentage saving on the energy bill with DSS in year m, $f_m(s_m)$ is a logistic function that models the adoption propensity in year m, and X_m is the fraction of floor space with DSS adopted by year m. The parameters for the logistic function are a, b, and c, which are estimated in Maribu et al. (2007) to be 200, 0.4, and 60, respectively. Similarly, α and β are parameters for the knowledge diffusion function. They vary depending on whether or not there is a government program in place to encourage diffusion. Thus, they are 0.02 and 0.98, respectively, in the baseline setting (and 0.1 and 0.9, respectively, in the program setting).

Using data from Petersdorff et al. (2005), we note that a conservative estimate of available floor space in EU15 countries with potential for DSS adoption is 797 million m^2. This consists only of non-residential buildings larger than 1000 m^2 constructed between 1975 and 1990. The rationale for this selection is that buildings of older (newer) vintage will have already been refurbished (will be relatively energy efficient). Hence, they may not be ideal candidates for a strategic DSS.

In Fig. 5, we plot the adoption propensity function with respect to percentage savings on the energy bill. It has the characteristic S-shape of a logistic function and reaches an asymptote for large s_m at about 60. This means that increasing the percentage saving in the energy bill beyond 30% is unlikely to make much difference to the adoption propensity.

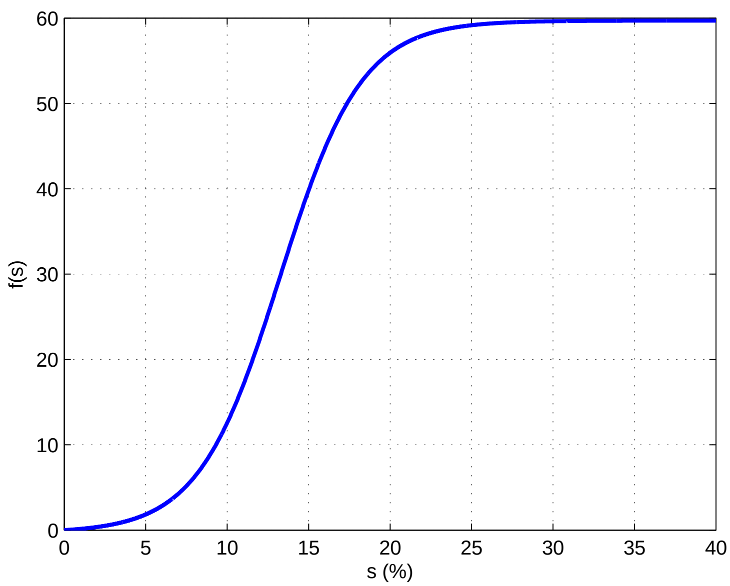

Figure 5: Adoption Propensity as a Function of Percentage Savings on the Energy Bill

Using the adoption propensity for $s_m = 10\%$ and $s_m = 20\%$, we plot the cumulative (D_m) and incremental (A_m) floor space that adopts the DSS in Figs. 6 and 7, respectively. Note that each figure includes curves with and without the effects of an outreach program. For example, for $s_m = 10\%$, the cumulative floor space adopting our DSS in EU15 countries reaches only 40 million m^2 by 2025, which is 5% of the area available in existing buildings. However, with an outreach program, this number quadruples to reach 20% of the available floor space. Hence, it is essential to have EU- and national-level dissemination events and awareness-raising programs.

The impact of the expected savings on the energy bill is also important. For example, with 20% expected savings (like at FASAD), it is possible for the DSS to be adopted by 85% of available floor space (Fig. 7) even without any special outreach efforts. The reason for this difference can be seen from the adoption propensity curve in Fig. 5: a doubling of the percentage savings from 10% to 20% more than quadruples the adoption propensity.

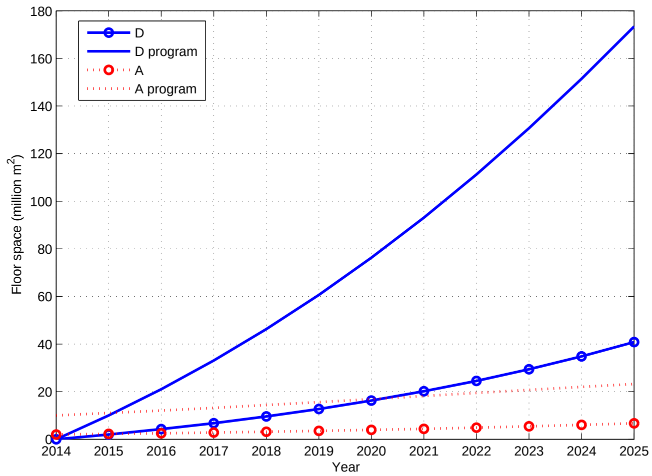

Figure 6: Cumulative and Incremental Floor Space Adoption of DSS in EU15 with 10% Energy Bill Savings

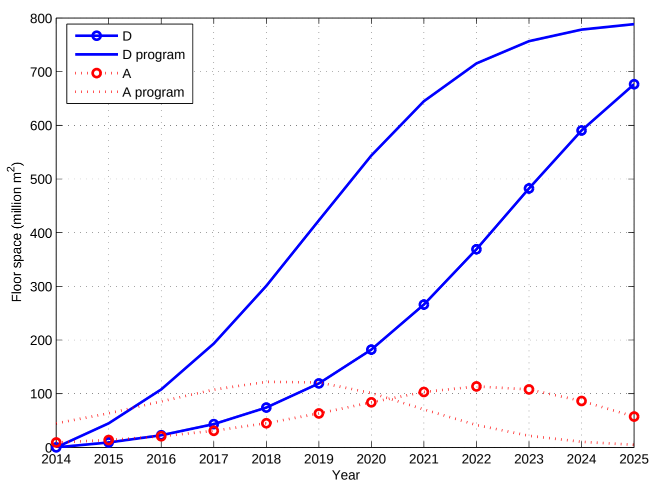

Figure 7: Cumulative and Incremental Floor Space Adoption of DSS in EU15 with 20% Energy Bill Savings