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1. Introduction

This deliverable has been developed as a part of task 2.3 of the ReUseHeat project entitled: Contractual Arrangements and Business Models for Urban Excess Heat Investments. The deliverable focuses on the following two areas:

1. dealing with risk in district heating.
2. funding and ownership of district heating.

This deliverable is one of three deliverables within task 2.3. Deliverables 2.3 and 2.4 focus on business models and contract design with the former focusing on general theory and applications and the latter focusing on the ReUseHeat demonstrators themselves. There is some overlap between the material presented within this deliverable and within the two aforementioned documents. Models of risk and funding have a significant dependence on the chosen business models and/or contract design creating a natural link between these concepts. Additionally, one of the roles of contracts is risk transfer and, therefore, the contractual models discussed in those deliverables are important vehicles for the transfer, sharing and allocation of the risk items discussed here.

This deliverable is presented as follows. The first three chapters focus on risk. In chapter 2, scenario analysis is discussed along with the closely related topics of stress testing and sensitivity analysis. The aim of the chapter is to review the use of scenarios and sensitivity analysis in infrastructure projects and their applicability to energy and, in particular, district heating. Areas of focus include the purpose of scenarios, uses of scenarios and scenario design. The UK National Grid produces energy scenarios on an annual basis and these are discussed in detail.

The discussion of risk is continued in chapter 3 which focuses on cognitive bias in infrastructure projects. Optimism bias, in which overly optimistic project assumptions are made at the planning stage, is thought to be a common cause of cost overrun and overspend in infrastructure projects. The chapter provides an overview of the contents of an academic paper written by the authors of this deliverable, which can be found in the appendix. The paper proposes a number of approaches to dealing with optimism bias in the modelling of infrastructure projects. The methodology is demonstrated in the context of a simple techno-economic model of a hypothetical district heating project.

Chapter 4 focuses more generally on risk and how it relates to district heating projects. Here, a large number of categories of possible risks to district heating projects are presented and, in each case, possible approaches to mitigation are discussed. Specific (anonymised) risk items identified by ReUseHeat demonstrators are then presented along with, where available, their chosen approaches to mitigation. Finally, the concept of risk sharing contracts is discussed.

The topics of funding and ownership are approached in chapter 5 in which, first, possible funding sources for district heating projects are identified and, second, different ownership models are discussed along with advantages and disadvantages for each.

In appendix one, each of the four ReUseHeat demonstrators is described. In appendix two, the UK National Grid’s energy scenarios are described and, in appendix three, the paper described in chapter 3 is presented.
2. Scenario Analysis

2.1. Introduction

Scenario analysis, Stress Testing and Sensitivity Analysis are three closely related techniques for assessing the impact of different underlying assumptions about the future. In Scenario Analysis, a set of scenarios is defined and the impact of each is assessed. Stress testing, a term which is often used interchangeably with Scenario Analysis, is a similar concept. However, here, the aim is to consider extreme scenarios to assess the impact of unlikely but high impact events. Sensitivity Analysis is closely related to both Scenario Analysis and stress testing. However, instead of defining scenarios, Sensitivity Analysis perturbs the model inputs or assumptions and analyses the impact on the model output(s).

The aim of this chapter is to review the three concepts defined above with a particular focus on Scenario Analysis and, to a lesser extent, Sensitivity Analysis. To illustrate each of the three methods, consider a case in which the designers of a district heating scheme want to assess the risk of an increase in the price of electricity to run a heat pump. This is generally considered to represent a significant risk to district heating schemes as electricity costs form a large proportion of the running costs of a heat pump. Assume that the designers have built a model that takes the price of electricity as one of its inputs and the internal rate of return (IRR) as an output. If the rate of return falls below a certain level, the operators will be unable to pay back any loans they have taken or provide a return to its funder(s).

In scenario analysis, a number of scenarios would be defined for the cost of electricity and the rate of return calculated for each, usually using a model. Stress testing, whilst still concerned with scenarios, aims to assess the impact of extreme cases. In this case, that would likely be a particularly high electricity price, or a sudden change in the price, that would be considered unlikely but plausible. Note that, in both scenario analysis and stress testing, more than one variable is often changed between scenarios, particularly if they are correlated. For example, the designer of a scenario may believe that a high electricity price would be driven by increased environmental regulations and may choose to define such a scenario to feature other related conditions such as increased subsidies for low carbon alternatives to gas heating such as district heating. Sensitivity analysis is less concerned with scenarios and considers the effects of perturbing the inputs or assumptions of a model. In the case outlined above, this would involve perturbing the electricity price and observing the impact on the IRR. Variables correlated with the electricity price may also be perturbed in ordered to assess the effects of underlying drivers such as changes in environmental regulations.

2.2. Sensitivity Analysis

Sensitivity Analysis studies the effects of changes in model inputs or assumptions on the outputs of mathematical models and can help to identify the key sensitivities in the model and therefore the biggest risks to a project. This can help improve resource allocation in terms of reducing or mitigating these risks. Sensitivity analysis can also be a useful tool for communicating risks. A tornado diagram, for example, is a chart showing ranges for different model outputs with the highest range at the top and the lowest at the bottom, thus resembling a tornado. Tornado diagrams are a simple and effective way to communicate the risks to a project in an intuitive way. Commonly, Sensitivity Analysis is carried out in a ‘one-at-a-time’ fashion in which only one input to the model is perturbed at a time.
One of the downsides of this approach is that it can be misleading when important input variables are correlated. Issues regarding correlations are much studied in finance.

Consider, for example, a sensitivity analysis for the profitability of a district heating scheme given different assumptions about future demand. Simply perturbing the assumption about demand levels may be misleading since other factors may be affected by the same underlying factors that affect demand. For example, an economic downturn may reduce heat demand but also result in the removal of green subsidies or increase inflation. The issue of correlated input variables has been considered and various approaches have been suggested to this problem \[1, 2\].

Sensitivity analysis is regularly used at the feasibility stage of district heating schemes. For example, a project aimed at using heat from Shoreham port in West Sussex, UK used sensitivity analysis to assess the impact of differing model inputs such as future heating costs, the price of electricity and capital and operating costs \[3\]. Assessing the impact of differences in these inputs allowed for some insight into the reliance of the project on underlying scenario assumptions. In a study aimed at informing energy policy for the London borough of Brent \[4\], a part of which was to assess the viability of district heating, Sensitivity Analysis was applied to assess the impact of factors such as the price of waste heat, the sale price of heat, the price of natural gas, maintenance costs and the price of electricity on the internal rate of return of the project. In a feasibility study for the use of excess heat from a heat shaft of the London Underground to heat local homes and businesses in Morden, South London \[5\], Sensitivity Analysis was applied to assess the effect on the IRR of factors such as heat demand, total CAPEX, heat prices and heat losses through the network. The UK Green Book scenario projections were used to assess the effect of differences in assumptions about the cost of gas. In \[6\], analysis was carried out to assess the effects of differing levels of energy efficiency in buildings connected to district heating Upsalla and Linkopping, Sweden. This was of interest since increased energy efficiency leads to a reduction in heat demand. As a result, sensitivity analyses were carried out to analyse the effect of differing heat demand and electricity prices.

2.3. Scenario Analysis

2.3.1. The Purpose of Scenarios

Scenario analysis varies in its ultimate aim which can typically be placed into two different categories. In the first category, often referred to as scenario planning, the aim of the analysis is to assess which future events are plausible, what knock on effects this could have and to encourage planners to think about the future and what risks/opportunities should be planned for. This sort of thinking is common in disaster planning, for example. The second use of scenarios is in decision making in which scenarios are used to aid a specific decision. This sort of scenario analysis is common in energy planning where, for example, the decision of how much energy is needed to meet demand might be asked.

2.3.2. Uses of scenarios

Scenario analysis is a process by which the effects of distinct plausible future scenarios are analysed. The rationale behind scenario analysis differs from that of forecasting in that the scenarios are not generally extrapolations of the past but are built on certain underlying assumptions about the future that are considered to be plausible.

Scenario analysis has been used in a wide variety of different fields. In 1973, Peter deLeon of the Rand Corporation wrote a report detailing his experiences of using scenario analysis in ‘games’ centred around political and military situations \[7\]. The games were designed with two ‘teams’ who were faced against each other and a game-manager in charge of setting various scenarios for the teams.
One of the main aims of the games was to put people in unpredictable positions to encourage them to practice their decision making in a difficult environment.

In disaster planning, the job of building scenarios is often given to a set of experts who then present those scenarios to decision makers who are asked to assess the effects and, crucially, potential mitigating action. This is commonly done in the planning for a potential nuclear accident, for example. The State-of-the-Art Reactor Consequence Analyses (SOARCA) project has been set up in the USA to provide realistic scenarios regarding potential nuclear reactor accidents [8]. Users are able to define scenarios based on their likelihood of occurrence whilst computer modelling is used to predict how a reactor might behave under such conditions [9].

Scenario analysis is also widely used in energy planning and modelling. Shell, for example, regularly produces scenarios regarding future energy supply and demand using their Global Supply Model [10]. The scenarios produced differ in their underlying assumptions regarding hard to forecast factors such as geopolitical events and improvements in technology. The UK National Grid also annually produces future energy scenarios on behalf of the UK Government [11] (see appendix for details). The scenarios make projections of quantities such as the price of natural gas and the cost of carbon taxes up to 2050. Details of the scenarios are also disseminated to the public and are available online [12]. The EU Reference Scenario produces its own energy scenarios which are typically used in decision making for EU-wide initiatives [13].

Scenario analysis is widely used in the planning and construction of infrastructure projects. One example is in the analysis of the potential effects of climate change. The IPCC (Intergovernmental Panel on Climate Change) releases regular reports on the state of the climate, including projections under a number of emissions scenarios. Downscaled versions of these projections are often used to inform, among other things, the likelihood of flooding [14] and future demand for air conditioning [15].

Scenario analysis has also been used in the planning of district heating. This has been done in assessment of the viability of district heating both on a wide scale and in the context of specific district heating schemes. For example, in [16], the viability of district heating as an alternative to gas fired CHPs in the UK was considered under the following four scenarios:

1. Scenario 1: Large-scale heat network retrofit with a central heat pump serving existing non-domestic buildings.
2. Scenario 2: Medium-scale low temperature heat network with a central heat pump and building-integrated heat pumps serving a new residential development.
4. Scenario 4: Small-scale low temperature heat network with a central heat pump and hot water-only building-integrated heat pumps serving a new residential development.

Note that, in this report and others, different infrastructure configurations are also referred to as ‘scenarios’ but do not refer to the kinds of scenarios used in scenario analysis. In work done for the National grid [17], the ability of district heating schemes to meet future demand was assessed under different heat scenarios. The scenarios used were the National Grid’s future energy scenarios mentioned above.

Scenario analysis has also been used to analyse the future performance of individual district heating schemes. For example, in [18], four scenarios were defined to assess the effects of greater energy price volatility and improvements in thermal storage on the future prospects of a district heating scheme in Borås, Sweden. This was done under four scenarios: (i) a reference scenario that assumes that the situation will stay roughly as it is, (ii) a scenario with greater variation in electricity generation as a result of increased production of renewables, (iii) a scenario in which the frequency of breakdowns in the district heating of the city is increased and (iv) a scenario in which the proportions of fuel used in
the current CHP are changed significantly. Scenarios often differ in the level of control that the decision maker has over them. Consider, for example, a municipality that wishes to decide whether to proceed with a proposed district heating network for the city. To help understand the risks associated with the decision, they decide to utilise a number of energy scenarios and assess their impact on the viability of the project. Some potential elements in scenarios will be out of the control of the city whilst, for others, there will be direct control. For example, changes in the wholesale electricity price cannot be controlled by the city and thus can only be mitigated. Subsidies for solar panels, on the other hand, might well be in direct control of the city. This distinction brings up a subtle difference in potential policy actions. Whilst, in the former case, the city can only mitigate, in the latter, they are able to directly impact the nature of external events to the project of interest.

A set of scenarios will often be used by a number of different stakeholders in a range of different settings, who will often have differing levels of control over that scenario. For example, the UK National Grid’s scenarios include assumptions about investment in green technologies. The government has a high degree of control over this whilst the developer of a small district heating network does not. This is an important distinction demonstrating the wide range of different uses of scenarios.

An important question regarding scenarios is whether they should be designed with a specific decision in mind. In nuclear disaster management, scenarios are typically designed specifically with the question of what preparations should be made. These scenarios are usually designed independently from decision makers to try and encourage thinking beyond what they might usually consider. Energy scenarios are often designed by a third party without the specific decision of interest in mind. The National Grid’s scenarios, for example, are built for use by the UK Government in its energy planning, but are also widely used in other decisions.

2.3.3. Designing Scenarios

The design of scenarios is extremely important in terms of providing useful analyses of potential future events. One approach to scenario analysis is to define optimistic, pessimistic and neutral scenarios. Scenarios may also be defined based on the occurrence of some underlying event (Britain voting to leave the European Union, for example). Whilst, in theory, any number of scenarios can be considered, in order to avoid overcomplication, it is often suggested that no more than three should be used [19]. In [20], a number of conditions for useful scenarios are defined in the context of climate related risk. These conditions, however, are also useful for designing energy scenarios including in the context of district heating. Each of the conditions is described below:

1. Plausible - a scenario should be plausible and there should be a narrative with justification for each event or change in underlying assumptions.
2. Distinctive - the different scenarios should be distinctive enough in terms of the key factors for there to be a clear difference between them.
3. Consistent - Interaction between key factors should be taken into account. For example, changes in the discount rate and heat demand may be correlated due to changes in a country’s economic situation.
4. Relevant - each scenario should be relevant in terms of giving a specific insight into the future (e.g. a local authority massively increases spending on green projects and subsidies).
5. Challenging - scenarios should challenge the conventional view on things that may affect the project in question.

An advantage of scenario analysis for the planning of district heating is that they are, or should be, easy to understand and can provide a clear and intuitive set of conditions on which a projection is based. Correlation of events can also easily be incorporated without the need for detailed mathematics. This is far less complicated than in sensitivity analysis in which the correlation would need to
be carefully defined if more than one input is allowed to vary at once. Correlations are also notoriously difficult to elicit in expert judgement exercises. The following factors are all considered to be among the biggest long term risk items in the construction of district heating schemes and should be considered for inclusion in scenarios.

1. Electricity price
2. Value of heat
3. Discount rate
4. Technology
5. Loss of demand

In designing scenarios, dependence between these factors will often be taken into account. For example, the value of heat is influenced by both supply and demand and so correlation between factors such as demand for heat and the price of heat will need to be considered. Likewise, in an optimistic scenario, it might be assumed that the electricity price will be low and that this is a direct cause of strong advances in technology used for electricity generation.

Another example of how scenario design might be approached is on the basis of different government reactions to tackling climate change. For example, in a scenario in which governments are expected to spend a relatively large amount of money on climate change mitigation, more money might be available for district heating subsidies whilst, on the other hand, a higher carbon tax may be applied to electricity, increasing the cost of running a heat pump. However, other ways of generating heat such as gas boilers may also be taxed higher making district heating more competitive. Clearly, then, the impact of different scenarios can be highly complex and care must therefore be taken to take into consideration as many important factors as possible.

2.3.4. Long Term v Short Term Objectives

Scenario analysis differs significantly according to the timescale of the decision to be made or action to be taken. Similarly to forecasting, the longer the time horizon of interest, the more uncertain the future. In the design of long term scenarios, such as in climate science in which scenarios can reach fifty years or more into the future, it can be extremely difficult to identify plausible pathways. For short term objectives, on the other hand, the task is often much easier and, in some cases, the same decision is made repeatedly.

Consider, for example, a case in which the objective is to ensure that a country is able to meet energy demand over the following two year period. This is a decision that will likely have been made regularly but is still subject to qualitative factors such as political changes or geophysical risks.

2.3.5. Uncertainty

A key question in scenario analysis is whether scenarios should come with any probabilistic estimate attached. The plausibility of this depends on a number of things. One particular problem is that is often difficult to design scenarios that span the probability space, that is provide an exhaustive set of possible outcomes. Consider, for example, a set of scenarios in which the electricity price is a factor. Typically, in each scenario, a specific price would be defined over time. In reality, it is highly unlikely that changes in the electricity price would happen exactly as described in any of the scenarios and therefore, placing a probability on any of them would be a difficult and, arguably, pointless task. This becomes even more difficult when multiple factors are varied in different scenarios. One way in which to attempt to avoid this situation is to define scenarios using different defined levels. For example, energy scenarios could be defined with a “high”, “medium” or “low” electricity price. This causes further complexities, however, as the question of how these translate into model parameters must be
determined. Even with a fairly simplistic set of scenarios, calculating the probability of each one can be extremely difficult, particularly when long time scales are considered. Dependencies between scenario elements can quickly make the calculations complex and probabilities inaccurate. Therefore, in many cases, the value of placing a probability on a scenario is questionable.

In some cases, the decision maker has some control over how a scenario develops. In this case, were the probabilities able to be calculated accurately, the actions taken by the decision maker may change those probabilities. This effect would complicate matters though it should be noted that modern option theory aims to answer the question of how to deal with such a situation.

Given the difficulty of assigning probabilities to scenarios, it is interesting to consider how the results should be presented in a decision making context. Inevitably, a decision maker will want to gain some insight into the relative likelihood of each scenario. If this is not possible, a solution is to perform analysis with each scenario and present these to the decision maker separately. Discussion of the relative likelihood can then take place whilst the decision maker themselves may be informed enough to have their own insight on the matter. One simple way of presenting the relative likelihood is to rank the scenarios in terms of their plausibility.

### 2.3.6. Least Worst Regret and Other Methodologies

In decision theory, Least Worst Regret (LWR) is an approach in which decisions are made with the aim of minimising regret. In the context of infrastructure projects, regret is defined as the difference in cost between the decision taken and the optimal decision. The difference is ‘regretful’ since the cost is ‘higher than it could have been’. LWR is often seen as practical because it doesn’t require estimation of the probabilities of different future scenarios. For example, in its Electricity Market Reform Report 2015 [21], the National Grid justifies the use of LWR by stating:

‘One benefit of this approach is that it is independent of the probabilities of the various potential future outcomes and therefore it can be used when the probabilities of these outcomes are unknown, providing that the cases considered cover a range of credible outcomes.’

LWR is built around the principal that humans tend to be risk averse and seek to avoid regret as much as possible [22]. The idea is closely linked to Prospect Theory which stipulates that the negative utility from a perceived loss tends to be higher than the positive utility from the equivalent gain. Regret is a powerful emotion with strong psychological effects. Additionally, regret can have a deep impact on the reputation of an individual or organisation where the risk of being responsible for a big ‘missed opportunity’ can be high.

In our opinion, the evidence underpinning the use of LWR is weak. Avoiding discomfort to the decision makers resulting from cognitive biases is not a sound basis for making a decision, nor is the seemingly deliberate attempt to avoid the use of probability. Likewise, whilst, inevitably, reputational issues will almost certainly have an impact in decision making, it seems odd to embed the biases of the decision maker in the methodology behind the decision itself. It would be much better for the decision maker to focus on justifying their decision more scientifically.

Whilst the fact that the LWR does not require estimates of probabilities is seen as desirable by some, it is not clear that the problem is adequately avoided. One criticism of LWR is that it can discourage the consideration of unlikely scenarios since there is nothing in LWR that differentiates likely and unlikely scenarios. If unlikely scenarios are omitted because they are considered unlikely, already, some assumption about the relative likelihood has been incorporated into the decision. The question of how that information can be used better then inevitably comes to mind.

### 2.3.7. Creative use of scenarios

Effective risk assessment requires creativity in order to identify potential future risks, particularly if the timescales are long. This is particularly important in disaster risk management where risks are constantly
emerging and, if ignored, can be highly damaging. A variety of different techniques can be used to encourage decision makers to be creative when identifying potential risks.

One way to encourage creativity is to try and immerse people in a situation as much as possible so that they can more readily imagine potential risks or opportunities. The use of games by the Rand Corporation in the 1970s was designed to give participants a stake in the decision to incentivise them to think carefully as to how the situation might pan out [7].

The onset of modern technology has enabled far more realistic depictions of reality. Virtual Scenario Planning [23], in which participants are placed into a virtual reality world and asked to make decisions in real time, is growing quickly in popularity. One of the main aims of virtual reality is that it enables participants to visualise different scenarios, creating a far more immersive experience than one in which the situation is simply described. Potential use of virtual reality in the planning of smart cities is reviewed in [24].

Creativity should be encouraged when attempting to identify the risks of building a district heating scheme. This is particularly important since the time scale of a district heating scheme tends to be long. There are a range of areas in which the future tends to be particularly unpredictable and therefore in which creative thinking is particularly useful. The political situation, for example, can be highly changeable given that elections generally occur every few years whether on a municipal, regional, national or even EU level. Assessing the manifestos of potential election winners allows for a greater understanding of how policy might change, for example.

### 2.3.8. Scenarios and Expert Judgement

Scenario design is a challenging process that can involve the identification of unprecedented future events. This requires a great deal of creativity and insight that may only be achievable with the input of experts. The benefit of asking experts to design scenarios is twofold. First, asking an independent party to design a set of scenarios separates scenario design from scenario planning. This discourages the tendency to design scenarios that planners are already familiar with and are confident that they can deal with. Second, an expert may be far better equipped to identify a wide range of different possible scenarios and, as a result, planners and decision makers should be in a better position to deal with future events.

Expert judgement can also play a role in estimating probabilities or simply ranking the likelihood of different scenarios. This is particularly true in estimating probabilities of qualitative events that are hard to model. Expert judgement, in this setting, typically involves the estimation of a probability distribution by one or more experts in a field. When multiple experts are involved, the question of how to incorporate all of this information into a decision or probability estimate is an important one. The Sheffield Elicitation Framework (SHELF) [25] provides extensive guidance on elicitation from multiple experts. The framework involves the following steps:

1. Each expert is asked to come up with an independent probability distribution.
2. The experts are brought together to discuss differences in their estimates and interpretation of evidence.
3. A ‘consensus’ distribution is formed.

A facilitator is employed who is an expert in eliciting opinion and collects opinions and guides the discussion. Even after discussion, it is often difficult for a consensus to be found. The role of a Rational Impartial Observer is to listen to all opinions and discussion and to come up with a final probability distribution.

Expert judgement has an important role to play in scenario analysis for district heating. Typically, scenarios constructed by external parties, such as the UK National Grid’s Energy Scenarios, are used in planning for district heating. Expert judgement is already used extensively in the creation of such scenarios. Typically, no probability distributions are placed on such scenarios, however, and it may be a matter of judgement as to which is the most likely.

### 2.4. Summary

Traditional risk analysis, as covered in chapter 4, often falls short of stress testing of the kind, for example, that banks and insurance companies are required to perform under national and European regulatory compliance. The district heating and cooling development is, or should be, embedded within national, regional or local energy planning. This makes scenarios covering energy at all levels of the utmost importance. One reason
for this is that long term investment is very vulnerable to major national and international events, be they geophysical, financial, cultural etc.

The main features of scenario use are scenario design, the relationship between scenario use and traditional risk, the need for holistic definitions of uncertainty beyond the more mathematical versions based on probability (although probability remains important), and the creative use of scenarios in brainstorming the possible futures.
3. Cognitive Bias

As part of the ReUseHeat project, a journal paper by the authors of this deliverable has been produced on the subject of cognitive bias in infrastructure projects with a particular focus on district heating. The specific bias of interest is optimism bias, which causes people tend to be overly optimistic in their assumptions. It is believed that optimism bias leads to a range of problems in infrastructure projects, in particular cost and time overrun. The paper is entitled ‘Probability distortion, with applications to investment bias’ and can be found in the appendix.

3.1. Introduction

Cognitive bias plays an important role in human decision making with hundreds of different inherent biases believed to exist [26]. Traditional economic theory often assumes that all actors act ‘rationally’ and therefore aim to maximise their utility when making decisions [27]. Behavioural economics studies the impact of psychological factors on classical economic theory [28]. Kahnemann and Tversky’s seminal paper on prospect theory in 1979 set out a theoretical basis outlining the distortion of probabilities and utility functions in the context of gains and losses in wealth [29]. Theories of cognitive bias divide broadly into two areas in the mathematical theory:

1. Inaccurate assessment of probabilities, or future events.
2. Definitions and results related to the concept of risk aversion.

In the basic work, it was ascertained by psychological experimentation that there is a tendency to overestimate small probabilities and underweight high probabilities. When it comes to probability distributions, as opposed to discrete probabilities, this can be translated into an upward distortion at the lower end of the probability distribution and a downward distortion at the upper end. Here, we are considering distributions for positive quantities such as a cost, efficiency etc. There are also two-sided versions which can be applied to distributions like the Normal distribution.

Given a ‘true’ probability distribution, for example one based on prior experience or observational data, the effect of the distortion arising from this kind of bias is to present a different cumulative distribution function (cdf) which will be higher for low values and lower for high values. The distorted cdf will typically cross the ‘true’ cdf exactly once. The aim is to distort the probability distribution to remove or reduce the underlying bias.

The mathematics of risk aversion shares with this probability distribution some features. Typically, the utility of an economic agent caused by a small financial gain will be higher than the financial gain itself whilst, for a sufficiently large gain in wealth, a diminishing marginal utility takes hold causing the marginal gain in utility to be smaller than the marginal financial gain. At some point, therefore, there is a crossover point at which this change occurs. A consequence of this is that, for example, the increase in utility from gaining £1,050 rather than gaining £1,000 is likely to be different to the increase in utility from gaining £50 rather than gaining nothing. Of course, since a utility function is subjective, different actors will react different to different gains or losses in wealth. It is these differences that define different levels of risk aversion in different economic actors.

3.2. Motivation: Cost and Time Overrun

Infrastructure projects are particularly prone to cost and time overrun which is often attributed to optimism bias among other things [30]. Several notable examples can be found in the United Kingdom. The Scottish parliament building, which was completed in 2004, cost £430m and took five years to build. This was significantly higher than the initial estimate of £40m and two years construction time [31]. More recently, the Crossrail project in London, at the time of writing, is expected to open nine months after its original schedule and run...
several hundred million pounds over budget [32]. Other notorious examples of time and cost overrun globally are Berlin Brandenburg airport (at least six years behind schedule and six times the initial cost [33]), Sydney Opera House (14 times the original estimated cost) and the Olympic games which, on average, have seen a cost overrun of 179 percent between 1960 and 2012 [34]. It has been estimated that 30 to 60 percent of UK infrastructure projects overrun in cost in the 1990s [35].

Factors that cause cost overrun have been the subject of a large amount of research. It has been suggested that cost overrun can be caused by both deliberate and non-deliberate factors. In the former case, evidence is presented by [36] that deliberate efforts to underestimate the costs of a project during the bidding process eventually cause the project to overrun. The same authors have argued that underestimating the costs during the bidding process can be rational when those who may be employed on a project are also involved in its appraisal. Optimism bias is believed to be one of the biggest causes of cost overspend [30] since it manifests itself in the planning and construction of infrastructure projects causing appraisers to be overly optimistic in their assumptions regarding the risks to a project. This, in turn, leads to overly optimistic assessments of revenue, costs and construction time. Flyvberg et al argue that a more accurate description for ‘cost overrun’ is in fact ‘cost underestimation’ [37].

3.2.1. Practical Debiasing

A variety of approaches have been proposed to combat optimism bias in infrastructure projects. These are summarised below.

3.2.1.1. Incentivising Accurate Appraisal

One approach to the reduction of bias is to improve the way in which risk assessment is performed. Underestimation of project risk can lead to unrealistic estimates of costs, revenues and construction times. If more risks can be identified at an early stage of the project alongside better evaluation of that risk, more informative estimates of cost and time can be found. One way to encourage accurate appraisal is to punish over-optimistic budgeting and incentivise accurate budgeting provides appraisers.

3.2.1.2. Group Risk Assessment

Key to project appraisal is to identify as many risks as possible and to accurately assess of their severity. Identifying risks, however, works best when people are able to think creatively. Encouraging a group of people to work together in risk assessment can help increase the number of risks identified as well as encourage more accurate assessment of the severity of that risk. A variety of different techniques have been proposed to elicit risk from groups. The Delphi Method, for example, designed with the aim of reaching consensus from a group of experts, can be used for assessing risk [38]. Under that approach, first, each participant is asked to assess the risks individually and, second, they are provided with the anonymised answers of the other participants and asked if they wish to reevaluate their responses. The group will often then come to some consensus; otherwise the process can be continued until they do. Brainstorming is another approach to group risk assessment in which participants work together in the same room to identify the risks [39]. This can help encourage participants to consider aspects that they may not previously have taken into account.

In risk assessment, it is often beneficial to try and immerse people into a situation in order to encourage as much creativity as possible. This is commonly done in Scenario Analysis to try and encourage identification of as wide a range of scenarios as possible (see chapter on Scenario Analysis for details).

3.2.1.3. Utilising Past Experience

During the financing stage of a project, experience of other, similar projects is often considered to be of value to funders. This is partly because, in this case, funders consider that more accurate appraisal can be done, thus reducing the likelihood of overly optimistic assessments. This experience is generally highly valued by banks who often set conditions for a more experienced project partner to take on a higher proportion of the risk.
One proposed approach to using past experience is Reference Class Forecasting (RCF) in which cost overrun is estimated from other similar past projects. The UK Treasury’s Green Book uses RCF by making recommendations for an additional percentage to be added to the calculated costs of a project [40]. These adjustments depend on the type of project and have been calculated based on the results of a report in which the cost overrun of a large number of projects was assessed [41].

3.2.1.4. Independent Auditors

Another way of reducing bias is to hire independent auditors to validate guarantees made by the project stakeholders [42]. Whilst those with an interest in getting a project funded may be incentivised to provide overoptimistic assessments, independent auditors do not have this incentive. This can be highly beneficial for project funders when considering whether to fund or not. The downside to independent appraisal is that the independent appraisers may be less incentivised to think as carefully about the risks if they will not be involved with the project in the longer term.

3.2.2. Paper Overview

The attached paper considers a different approach to dealing with optimism bias in which inputs to models are adjusted. In mathematical modelling, it is common to represent uncertain inputs to models as probability distributions and to assess the effect on model outputs using simulation. This process is called sensitivity analysis. Consider, for example, a simple model of a district heating scheme in which the exact coefficient of performance (COP) of a heat pump is not known until the project is in operation. In such a case, the uncertainty in the model input can be described by a probability distribution. However, inherent bias may cause overoptimism when defining that distribution. The aim of the methodology in this paper is to distort such distributions to attempt to remove, or at least reduce, this bias. This paper proposes a number of approaches to the distortion of probability distributions with this aim. Each approach is simple, accessible and based on solid mathematical theory and thus provides a practical approach to dealing with optimism bias in the modelling of infrastructure projects.

The distortion functions described in the paper each have desirable properties in terms of distorting distributions. For example, one approach provides a distortion such that the distorted probability distribution retains its original distribution but with different parameter values.

The distortion methodology is demonstrated on a simple techno-economic model based on a district heating scheme with the parameters broadly based on information collected from the ReUseHeat demonstrators. The model is used to propagate model inputs represented by different probability distributions of the Coefficient of performance (COP), the electricity price and the discount rate through the model to assess the impact on the net present value (NPV).

3.3. Summary

The failures of rather mechanistic models of economics based on restricted versions of rationality has led to celebrated work in behavioural economics. In summary, this is a recognition that humans make unsound judgements, which come under the general heading of bias. This is particularly serious in infrastructure projects and arises from misjudgements, particularly about costs and income but, also, other, more detailed, parameters such as discount rate and prices. Extensive studies have shown the prevalence of bias and these ideas are now incorporated into national treasury recommendations.

Theory is one thing but practical methods to get over bias need to be promulgated. These divide into two categories. First, traditional spreadsheet based risk modelling needs to be widened to facilitate input deviations to reflect bias. This is the subject of the attached paper. Also listed are methods of management style. Ideally, these methods are preventative but also need to mitigate contract deviations when they occur. Although the demonstrator projects have not directly attacked the issue of bias, two methods already used could be listed under this heading. The first is to use contractors with proven experience which can help with benchmarking
and, second, to have some form of independent body to audit guarantees. Such methods are often covered under a mitigation heading in risk analysis.
4. Risk in District Heating

Risk can broadly be defined as a scenario in which there is some possibility of losing something of value. That something of value can be wealth, time, health, or anything else that can be assigned a value. More formally, the risk exposure of an individual item is usually defined as risk = loss \times \text{probability} and therefore the size of the risk can be interpreted as its expected impact. The aim of this chapter is to discuss risk in the context of district heating projects. Firstly, categories of risk affecting district heating projects are reviewed. Secondly, the approach to risk taken by the ReUseHeat demonstrators is reviewed and a list of identified risks is given. Thirdly, the topic of risk allocation is discussed in the context of district heating. Finally, the relationship between risk and bankability in district heating is discussed.

4.1. Types of Risk in District Heating Projects

In this section, categories of risk related to district heating projects are identified and discussed. In each case, possible approaches to mitigation are described.

4.1.1. Engineering Risks

Engineering risks are risks related to the engineering of a project such as design and construction faults, i.e. mistakes made during the design and/or construction of the required infrastructure of equipment. Engineering risks can cause increases both in terms of the timeframe and the cost of a project and so effective mitigation can be highly beneficial. To mitigate this type of risk, the designer and manufacturer of the infrastructure should be incentivised to minimise the probability of such problems. One way to do this is to ensure that the cost of such mistakes is borne by the designer/builder. Modern technology can help reduce the risk of design faults. Virtual reality (VR) design tools can now allow designers to ‘see’ how a finished project might look, allowing them to iron out mistakes before the manufacturing or construction stage [43, 44].

4.1.2. Project Risk

Project risks are risks related to the design and running of a project. Common examples of project risk are cost and time overrun which tend to result from overly optimistic assessments at the planning stage [30]. Other examples include turnover of skilled staff, skill shortages and generally poor management. The risk of cost and time overrun can be mitigated by taking steps to reduce overoptimism in project planning. This is discussed in detail in chapter 3.

Another form of project risk is asymmetric information between project partners. For example, typically, an excess heat provider does not have a good grasp of the value of heat and how its value changes over time (e.g. in relation to the weather). Additionally, a district heating operator may have a poor understanding of the industrial processes of the heat provider. This can be a risk if the project partners make inaccurate assumptions about each other’s ability to buy or provide heat.

A feature of district heating is that the project lifetime is usually long. This means that, when multiple project partners are involved, long term contractual arrangements are required. This is a risk and usually requires a high degree of trust between partners. The risk is typically reduced if the partners have an existing business relationship and/or expect to form a partnership in the future since, in that case, all partners have an incentive to maintain good relations.
4.1.3. Operations Risk

Operations risk relates to the risks that can occur during operation. Examples of operations risk are poor maintenance, underestimation of maintenance costs and time, and pressure to replace technology with more expensive modern alternatives. One way in which operations risk can be mitigated is to use modelling in order to better understand the kinds of problems that might occur and to consider ways in which this might be dealt with.

4.1.4. Demand/Revenue Risk

Demand risk represents a significant risk to district heating projects. Worse than expected demand can stem from a range of sources. One cause of demand risk is from improved building/insulation. It is common for governments to provide subsidies for insulation and thus the money spent by on this can have a strong impact on the quality of insulation and therefore on heat demand. Another demand risk for district heating is competition from other suppliers of heat. If a cheaper source is made available or provided with a subsidy, users may choose not to be supplied with district heating and, instead, to be supplied with that source instead. Poor customer relations and reputational issues can also suppress demand for district heating. The latter issue has been a particular problem in the United Kingdom in which there have been several high profile cases of customers being stuck with long term contracts and no right to switch to an alternative provider [45]. Climate change represents another risk in that increased temperatures could lead to decreased demand for heating. Demand risk can be mitigated in a number of ways. One way is for governments and local authorities to oblige customers to sign up to district heating so that they cannot legally switch to an alternative source of heat. This, however, risks poor customer relations, particularly if cheaper sources of heating are available to other members of the public that are not available to them. In risk modelling, political issues like changes in regulation and subsidies can be hard to quantify and consider in a model. One approach to understanding the risks better is to consider different scenarios for different policy decisions.

4.1.5. Supply Risk

Supply risk, in the context of district heating, relates to risk items that may affect the supply of heat. Since district heating relies on excess heat from external sources, cessation in the ability or willingness to provide that heat, such as changes in owner and cessation in operation, pose a large risk to district heating schemes. Other supply risks include a lack of extra heat to extend the network and volatility in electricity prices which can significantly increase the cost of providing the heat via a heat pump. Temporary outages in the supply of heat can also be a significant risk.

The risk of a cut off in the supply of excess heat can be mitigated in a number of ways. Examples include writing carefully worded contracts so that supply continues unhindered and providing incentives to the excess heat supplier to ensure that they continue to be happy with the arrangement. A backup heat supply, such as generators, can reduce the risk caused by temporary outages significantly. On the ReUseHeat project, all projects have a backup heat supply and thus the risk of temporary outages is low.

4.1.6. Environmental Risk

Environmental risks are those that are related to the environment and can include risk caused by the environment itself and risks to the environment. An example of environmental risk is unforeseen environmental impacts during the construction and operation of the project having have a knock on effect on environmental regulation, which can increase costs.

4.1.7. Financial Risk

Financial risk can impact the financing of a project. District heating can carry a wide range of financial risks, particularly given the typical lifetime of such projects. Typically, when the viability of a project is assessed, a number of financial assumptions have to be made. If these assumptions prove to be inaccurate, this can be
highly damaging to a project. Examples of quantities about which assumptions usually have to be made are listed below:

1. discount rate
2. interest rate
3. exchange rates

Uncertainty in cash flows also poses a financial risk. For example, in district heating, this might occur if payments for heat are not made on time due to financial difficulties by a project partner or end user.

Macroeconomic effects can also have a big impact on a project. Recessions, for example, may lead to a raft of problems such as reduced demand for heat, reductions in subsidies, increased inflation and failure of financial institutions.

Financial risks can be mitigated with careful financial planning. Commonly, conservative estimates of financial assumptions are made in an attempt to avoid overoptimism. The downside of this, however, is that estimated financial indicators give a potentially worse picture than necessary, risking the project appearing unviable.

4.1.8. Natural Disaster Risk

Natural disaster risk is risk stemming from natural hazards that can have a disastrous impact in terms of loss of life and/or economic damage. As such, disaster risk usually occurs as a result of extreme events such as electrical storms, floods and landslides. Events such as these can have a profound impact on district heating schemes in the form of damage to infrastructure. Natural disaster risk can be mitigated by purchasing insurance.

4.1.9. Performance Risk

Performance risk refers to risk associated with worse-than-expected performance. For example, in district heating, the Coefficient of Performance (COP) might be worse than the assumed value at the planning stage and so the overall cost of electricity higher than anticipated. In practice, quantities such as this are often estimated conservatively to attempt to avoid this risk. This, of course, has an effect on the economic indicators estimated for the project and can thus reduce the viability.

One way of mitigating performance risk is to purchase insurance. Insurance companies such as Munich Re provide energy efficiency insurance that pays out an agreed sum when energy efficiency targets are not met [46]. This could be purchased to mitigate the cost of a heat pump performing with a lower COP than would usually be expected.

4.1.10. Legal Risk

Legal risk refers to risks related to potential liabilities and obligations. Legal risks can cover a wide variety of different areas. For example, for any organisation, there is the risk that another party will take legal action and demand compensation for some financial loss. In the United Kingdom, various disputes between operators of district heating and customers have taken place as a result of differences regarding costs and compensation paid for outages [45]. There is potential for such disputes to grow and for district heating companies to be required to pay large sums of money to customers. District heating often locks customers into long-term contracts and this poses a risk if the legality of these contracts is challenged.

4.1.11. Regulatory Risk

Regulatory risk refers to risk resulting from the introduction of and changes in regulation. The district heating sector is relatively new in many countries and so little regulatory framework exists. This creates risk due to the uncertainty in how the industry may eventually be regulated. In mature markets such as in Scandinavia, in which district heating is well established, regulatory frameworks are far more likely to exist, although this varies significantly between countries. There is much more regulation in Denmark than in Sweden, for example, where a conscious decision has been made by the government not to heavily regulate the industry [47]. In either
case, regulatory risk may be lower since politicians have made a decision, perhaps by consensus, as to whether or not to regulate the market.

In countries in which district heating is less well established, there is often little regulation. As district heating becomes more relevant, however, a regulatory framework is likely to emerge. This represents a significant risk since a number of possible scenarios regarding regulation will need to be considered. There is, however, a potential benefit in operating in countries with little regulatory framework for district heating because the district heating sector may be able to work with the government in shaping these regulations. It is often far easier to build regulations from scratch rather than to amend existing ones.

Changes in regulation are potentially highly costly. For example, new environmental regulations may require the operators of a district heating network to purchase new equipment or new regulations on the use of fossil fuels may push up the costs of heat recovery.

Regulatory risk can be mitigated by creating dialogue with governing bodies and regulators. This allows dialogue and for the point of view of the district heating operators to be put across. An organised way of doing this is through district heating associations which can act on the behalf of its members. The Danish District Heating Association performs this role, among others, for district heating owners and operators in Denmark [48].

4.1.12. Political Risk

Political risk describes those risks related to political changes. Examples of this include changes of government and civil unrest which can both have a knock on effect on the economy and cause direct problems such as damage to infrastructure.

4.1.13. Ramp-up Risk

Ramp-up risk refers to risks associated with ‘ramping-up’ of production. In terms of district heating, this is usually risk associated with extending the network or increasing the amount of excess heat supplied to the existing network. One example of ramp-up risk is that there may not be sufficient excess heat to provide for extra customers and the potential opportunities to be gained from economies of scale may be lost. This risk can be mitigated discussing the possibility of ramping up heat recovery at an early stage of the project.

4.1.14. Competitive Risk

District heating can usually be considered to be a natural monopoly since high infrastructure costs would make it highly uneconomical to build multiple competing heat networks to service the same potential customers. Unlike gas and electricity infrastructure, it is not currently possible to transport hot water long distances without it losing its value. As a result, it is generally not feasible for multiple competing suppliers to use the same pipes to deliver heat (conceivably, competing heat sources could be utilised in the same district heating network, however.) Nevertheless, district heating companies face competition from alternative sources of heating such as gas, oil burners and electric.

Competitive pressures from alternative sources of heat are a significant risk to district heating schemes. This is particularly true because it can be hard to predict developments and the emergence of alternative sources over long periods of time. Consider, for example, a case in which air source heat pumps for individual properties become far cheaper to produce than at present. This could encourage more potential district heating customers to install this technology, reducing the viability of the project.

4.2. Risk Monitoring and Mitigation in ReUseHeat

The ReUseHeat Project features four demonstrators for the recovery of low temperature excess heat. These are as follows:

1. Brunswick: Waste heat recovery from a datacentre
3. Nice: Waste heat recovery from sewage
4. Bucharest: Waste heat recovery from a metro station

Note that the Bucharest demonstrator pulled out of the project and will be replaced by a project to recover heat from a Berlin metro demonstrator. Details of each demonstrator can be found in the appendix.

It was decided early on that the ReUseHeat demonstrators would agree on a standard approach to monitoring risk. The following process is taken so that the risks to all projects are regularly monitored:

1. Information is collected from each demonstrator on a monthly basis regarding possible risks.
2. Deviations from initial plans are to be identified and disseminated.
3. Mitigation is applied where necessary.
4. Each mitigated risk is followed up.

To follow the aforementioned steps, a number of risk monitoring tools were developed. Demonstrators are asked to fill in the template shown in figure 4.1 which details the risk, the type of risk (out of a number of categories) and numbers signifying the probability and impact of each risk. Both the probability and the impact of each risk is assigned a number between 1 and 4 with the numbers signifying the following descriptions about each:

1. low
2. moderate
3. high
4. very high

The overall risk priority is calculated by multiplying the two numbers together. The risk matrix is shown relating the probability and the impact of each risk is shown in figure 4.2 where the colour of each entry represents the overall size of the risk.

![Figure 4.1: Risk template for ReUseHeat demonstrators.](image-url)
4.2.1. Identified Risks

A number of risks were reported by each demonstrator in the template described above. Although information regarding which demonstrator reported the risk, details of that risk and the overall assessed size of the risk are confidential, an anonymised description of each reported risk is given below. Where appropriate, the approach to mitigation is given.

1. **Failure to agree terms between partners.**
   Preliminary discussions with alternative potential partners. Attempting to solve potential barriers to agreement.

2. **Failure to agree transfer of responsibility for financial issues.**
   Attempting to solve financial issues.

3. **Not meeting deadlines due to bureaucracy.**
   Review of technical and legislative requirements to minimise risk of delay.

4. **Unforeseen difficulties from novelty of the project.**
   Review of equipment and technical characteristics.

5. **Difficulties with interpretations of contractual clauses.**
   Clarify technical, financial and legal aspects of contracts with all partners.

6. **Inaccurate information provided in the tendering process.**
   Ensure that those responsible for drawing up tender documentation have sufficient experience in this area.

7. **Lack of bidders at procurement stage creating unhealthy level of competition.**
   Try to encourage media coverage. Ensure that technical details are available to as many potential bidders as possible.

8. **Overly optimistic estimates of project time.**
   Verify that all stages can be completed by necessary deadlines. Attempt find ways to avoid red tape.

9. **Failure to include important contingencies in contractual arrangements.**
   Try to ensure that all important details are included in contracts.

10. **Problems with logistics at project site.**
    Recheck equipment installation plans.

11. **Problems with working conditions at site.**
    Measures to protect staff.

12. **Delays due to design faults or equipment inadequacy.**
    Ensure that performance guarantees by manufacturers are in place.

13. **Delay in installing monitoring equipment.**
    Ensure contract with contractor ensures this is done in a timely manner.

14. **Project unexpectedly not eligible for public subsidies.**
    Emphasise environmental benefits and disclose technical and financial plans.

15. **Delay in construction planning.**
    Ensure the public authority provides timely information regarding planning rules.
16. **Delay in construction.**
   Ensure close interaction with local authority.

17. **Overly optimistic budgeting.**
   Review policies of contractor and contractual arrangements.

18. **Overly optimistic cost assessment.**
   Improve gathering of information and increase number of site reviews.

19. **Oversizing of system.**
   Cross comparison with similar projects.

20. **Not enough users sign up to solution.**
   Test subsets of potential clients to assess interest.

21. **The heat source ceases to provide excess heat.**

22. **Agreement is not reached with the developer.**

23. **New buildings will not be occupied.**

24. **Delay in availability of heat source resulting in inability to supply end-user.**

25. **Malfunction/inefficiency in the heat pump.**

26. **Unable to sufficiently monitor project.**

27. **Exceedance of local noise regulations.**

28. **Excess heat lower temperature than originally expected.**

29. **Delay in obtaining permission from authorities.**

30. **Delay in receiving material/equipment.**

31. **Problem integrating heat source into existing network.**

32. **Lower heat pump performance than expected.**

### 4.3. Risk Sharing Contracts

In a forthcoming deliverable, considerable attention is paid to the issue of contract design and how, in particular, good contract design should be based on sound quantitative modelling, including the sensitivity and scenario analysis discussed in this deliverable.

Many contracts are necessarily incomplete because of the complexity of the fact that not every event can be foreseen. Despite this, it is advantageous that basic risk items are recognised in the contract and this includes the allocation of the risk to a suitable party (stakeholder) with some understanding of the mitigation and its cost [49]. Thus risk sharing covers the issue of who should bear the cost of the risk, if the risk events occurs.

The basic terms of a capital project are (i) the contractor must complete the work on time and on budget (ii) the mechanism (arbitrator, court, insurance etc) in the event of (i) not being met (iii) the evidence required in this case.

The above considerations have led to the establishment of some basic rules:

1. If a risk is foreseeable then it should be itemised and allocated to the stakeholder best placed to assess, prevent, control and mitigate it.
2. If no stakeholder can assess prevent or mitigate this risk then it should fall on the stakeholder best placed to insure against it, or have access to equivalent funds.

There are other principals related to economic and moral aspects of risk sharing, which may not always be compatible:

1. The risk-sharing structure should encourage technical and economic efficiency.
2. There should be some element of fairness or equity.

An important concept in risk-sharing contracts is variation. Ideally a variation (renegotiation) may take place when both sides will benefit, as opposed to one-side situations which would only benefit one part. In that the latter case a variation may be allowed if it efficiency is increased or to induce an improvement in behaviour.
Complications arise from issues such as (i) the description of the information, and the ability to acquire to information, to verify a situation leading to a variation: burden of proof (ii) the nature and appointment of independent auditors or arbitrators to assess the situation.

Risk sharing contracts have been the subject of some quite theoretical work in economics, under the heading of the economics of contracts. In particular, with regards to the balance between incentives and risk [50, 51]. The importance of monitoring contracts is stressed in [52]:

“...if the public body is receiving a heat supply, it should ensure that: service standards are maintained by enforcing the KPI regime; the price review mechanism is properly applied; there is a clear contractual basis for any claims; and that any contract variations are duly authorised and recorded in writing.”

In the UK, the overall contractual arrangements area described in a “Heads of Terms contract”. These cover all contractual issues such as: shareholder agreement (for SPV/ESCo), warranties, insurance, compliance (to regulations), supply agreements and ownership. The main document is usually completed with important “boilerplate” clauses which cover amendments, variations, the role of third parties, dispute resolution and so on. They are a first line of defence in handling the contractual arrangement to better define the relationship between stakeholders and minimise risk. A more detailed “Risk-Sharing Contract” or “Risk-Sharing Agreement” would deal with the more detailed risk allocation responsibilities.

In deliverable 2.3, which covers contracts, the role of techno-economic modelling will be emphasised and it is expected that the relationship between modelling and risk sharing will be visited in more detail [53].

**4.4. Towards Bankability**

The bankability of a project, that is the likelihood of getting a bank or investor to fund it, is strongly linked to the inherent risks discussed in this chapter. Generally, to get a bank to agree to fund a project, it must be convinced that it is likely to get its money back along with a healthy return.

Deliverable 2.2 of the ReUseHeat project concerns the bankability of urban waste heat recovery. Figure 4.3, reproduced from that deliverable, demonstrates the process that banks typically go through in assessing the bankability of a project. Each of the four stages are described under the following headings (see deliverable for more details).

![Figure 4.3: Bankability Assessment for Project Financing](image-url)
4.4.1. Qualitative Risk Assessment

At this stage, information about the project partners (proponents, investors, technology providers, EPC contractors, clients, etc.) and their suitability is evaluated. The maturity of the technology and legal and technical frameworks are assessed along with any previous experience the bank has with the chosen technology. At this stage, the bank must decide whether or not to proceed with more formal quantitative risk assessment.

4.4.2. Quantitative Risk Assessment

Here, a more detailed analysis of the risk is carried out. This is based on the evaluation of technical design documents, contracts, licenses, etc. and is carried out by qualified experts within the bank or, if appropriate, private consultants. The aim here is to identify the risks and quantify their impact on the cash flow model.

4.4.3. Default Risk Assessment and Monitoring

At this stage, more detailed risk assessment is performed and a risk rating is assigned to the project. Tools such as sensitivity analysis are typically used.

4.4.4. Finance Structuring

At this stage, specific conditions of the loan, such as the interest rate, are decided based on the outcomes of the previous phases such as the risk rating. An offer is then made to the borrower.

4.4.5. Risk and Bankability

To understand bankability, one must appreciate the importance of risk in the financial sector. Indeed, banks themselves have very strict compliance regulations which are defined to a detailed technical level. For example, the term Value-at-Risk describes critical values of reserves or asset losses beyond which the institution would not be solvent. Under regulations, risks are divided into various categories such as liquidity risk and operational risk. Within the banking structure, also, risks are divided into tiers. Tier one, for example, means that the bank is first in line for repayment in the event of a default. Parcelling together stocks, shares or assets into various bundles allows a financial institution to produce complex financial instruments (some of these became notorious during the world financial crisis). It is difficult for outsiders to fully appreciate the central position of risk. A colloquial way of describing operations in financial institutions is the buying and selling of risk.

If the above is understood, it is important that where a city, or other sponsor, is putting together a business case for funding, that the risk analysis carried out, as explained in this document, and in deliverable 2.2, reflects, as far as possible, the main principles of risk analysis. This is because the financial institutions will use the same principles, although they may have additional principles related to the internal asset structure. It should be favourable if the financial institution has an infrastructure division which is already familiar, if not with district heating itself, then with other energy related projects.

In some cases, advice about what is expected is given by the banks themselves. For example, the European Investment Bank provides an ‘advisory hub’ that gives guidance on all steps of a project. JESSICA (Joint European Support for Sustainable Investment in City Areas) is an initiative of the European Commission which has been developed in co-operation with the European Investment Bank to provide guidance on applying for EU structural funds; this is useful for loans for smaller projects. In a situation where a financial institution is not very familiar with district heating, special guarantees may be necessary to convince the bank to lend and these guarantees are predicated on a special type of project. For example, in a changing and competitive urban environment, it may be difficult to both predict and to manage future demand. The competitive and rapidly changing energy environment is also likely to effect district heating to the extent that it will be of concern to the funders of projects. As financial institutions are themselves asked to stress test their reserves and individual instruments against scenarios put forward by the regulators, it is our recommendation that the use of...
scenarios to cover the insecurities in demand and the energy market will be useful (see appendix for details on energy scenarios). Finally, district heating may be vulnerable to specific technological advances (these could be captured by scenarios). Three of the most obvious are reduced costs of generating electricity, cheap storage of electricity which would make solar panels more competitive and developments in local domestic heat pumps (ground source, air source etc).

In summary, it is the responsibility of the city or sponsor to (i) be familiar with the main principles of risk analysis, (ii) have some familiarity with the market for loans as seen from a banking perspective and (iii) draw attention in business cases of the special nature of risk related to district heating.

4.5. Summary

Risks associated with capital projects, and district heating and cooling in particular, are well rehearsed. They are typically based on spreadsheets with additional soft system tools such as risk matrices and risk allocation tables. Perhaps the key idea, which is not always fully developed, is the dependence of the global risk picture on the allocation of risk to different stakeholders. Thus, technical risk is well covered and well understood, essentially because of its long history in civil engineering and related areas. The same goes for purely financial risk, which can draw on the huge developments in quantitative finance. Other areas of risk are less developed and we have identified three that fall into this category: risk due to cognitive bias, the use of scenarios and the representation of risk allocation in risk sharing contracts. Our advice, and also our predictions are that there will be great emphasis on these.

The ReUseHeat project has a major aim: the consolidation of both traditional and these newer areas of risk into the bankability, that is to make sound business cases to financial institutions of various kinds. The relationship between risk and bankability is discussed in the previous section.
5. Funding and Ownership of District Heating

The funding of district heating schemes represents a significant challenge creating perhaps the largest barrier for new projects. However, in recent years, innovative funding opportunities have been emerging which have the potential to fund district heating. In the first part of this chapter, we discuss potential sources of funding with particular focus on sources in which there is evidence of either a willingness to invest or actual examples of when a district heating scheme has been funded in this way. Funding is closely linked to ownership. In the second part of the chapter, we review a number of ownership models and list the pros and cons of each one, linking them to the specifics of district heating. The topic of ownership models will be revisited in deliverables 2.3 and 2.4, which focus on contracts and business models and are to be submitted in June 2019. Here, the question of ownership will be directly linked to the business model of choice and how this impacts the type of contractual arrangements required.

5.1. Potential Sources of Funding

In this section, potential sources of funding for district heating are reviewed. In each case, where applicable, examples of cases in which each source of funding has been used for district heating are discussed.

5.1.1. City/Regional/National funds

Public funds provide infrastructure projects with funding with required rates of return that are much lower than would be expected from a private sector funder. This allows projects that would otherwise not be feasible to be funded. A variety of such funds exist in various public entities and cover a number of different types of project. Some funds specifically cover district heating. Funds of this type include but are not limited to the following.

5.1.1.1. Scottish Government’s Green Infrastructure Strategic Intervention

The Scottish Government’s Green Infrastructure Strategic Intervention [54] aims to improve urban green space in Scottish cities. The fund aims to invest in 10-15 projects with a total outlay of £7m. The fund supplies match funding which means that the project must match the investment supplied by the fund.

5.1.1.2. ADEME Fonds Chaleur (France)

The ADEME Fonds Chaleur [55] is a French infrastructure fund aimed at investing in renewable energy and energy recovery and, as such, district heating schemes are eligible for funding. Between 2009 and 2016, the fund has invested 1.6 billion euro in 4000 projects.

5.1.2. Scottish Government’s district heating loan fund

The Scottish Government’s district heating loan fund [56] provides low interest loans of up to £1m to fund district heating with repayment terms of 10 to 15 years. Eligible entities for funding are local authorities, social landlords, small and medium sized enterprises and energy service companies (ESCOs) with fewer than 250 employees. At the time of writing, around £15M has been loaned to 50 different projects across Scotland since 2011.
5.1.3. Re:Fit (England and Wales)

RE:FIT is a project with separate branches for London, the rest of England and Wales that provides funding to help make non-domestic public buildings and assets more energy efficient [57]. The fund has invested around £165m so far in energy efficient projects over the three branches.

5.1.4. The Mayor of London’s Energy Efficiency Fund (MEEF)

The Mayor of London’s Energy Efficiency Fund (MEEF) [58] is a £500m energy fund funded by the European Regional Development Fund (ERDF). It is a follow up to the London Energy Efficiency Fund (LEEF) which ended in December 2015. The fund aims to invest in energy efficiency projects in the London area. At least seventy percent of funding must be allocated to the public sector. Projects are eligible for funding if the investment is over £1m. The target of the fund, however, is to provide investments of between £3m and £20m per project. The fund will run for a total of twenty years which is much longer than many similar funds and allows the funding of long term projects such as district heating schemes. MEEF has made available up to £2m to help support the business case for a project, with the aim of speeding up the due diligence process required to apply for funding.

5.1.5. Green Bonds

Green bonds are bonds specifically designed to fund ‘green’ projects that contribute towards reducing carbon emissions. As such, district heating schemes are generally eligible for funding from this type of source. The issuance of green bonds has grown a great deal in recent years with global issuance estimated to have grown to 130 billion dollars in 2017 [59]. The huge growth of green bonds is demonstrated in figure 5.1 (source:bloomberg) which shows the global issuance of green bonds between 2008 and 2017. Corporate responsibility has become a bigger issue in recent years with the proportion of the world’s 250 biggest companies reporting corporate responsibility data in their annual reports reaching 78 percent in 2017 [60]. The issuance of green bonds may therefore be attractive to companies with corporate responsibility targets. In addition, green bonds often come with tax incentives designed to encourage green investments. Green bonds often provide funding for large projects, typically much larger than district heating schemes. As a result, it may be beneficial to aggregate different schemes into one larger investment.

![Green Bond Boom](source:Bloomberg New Energy Finance)

**Figure 5.1:** Global issuance of green bonds from 2008 to 2017.

5.1.5.1. Green Bonds in Gothenburg

In 2013, Gothenburg was the first city in the world to issue green bonds with the aim of supporting environmental projects on public transport, water management, energy and waste management. The initial issuance in 2013 was 50 millions euro with a further 170 million euro issued in 2014 and 95 million euro in 2015. The
bonds were used to fund a district scheme in the city of Gothenburg in which excess heat from a passenger ship is connected to a local district heating network as part of the CELSIUS project. Gothenburg was awarded for its green bonds in the Green Bond Awards in 2016 [61]. The city of Gothenburg aims to be as transparent as possible and share its knowledge with other cities [62].

5.1.6. Contractors

Contractors such as Engie and Veolia often fund, build and operate district heating projects in their entirety. The funds to do this, in these cases, often comes from existing funds within the company with the advantage that financing costs are reduced (with any investment, there is of course an opportunity cost in that those funds could have been spent elsewhere). Veolia, one of the biggest contractors for district heating globally, operates over 100 district heating schemes around Europe. Another large company, Engie, operates over 180 schemes throughout Europe [63].

One of the benefits of district heating schemes that are run by big contractors is that these companies tend to have extensive knowledge and experience. This helps reduces the time and money that is required to be spent on transfer of knowledge and, at least in theory, reduces risk since experienced contractors are usually less likely to make costly mistakes due to their extensive experience. Contractors, however, are often reluctant to take on the risk of new types of project and thus will not usually fund pilot projects. European projects like ReUseHeat and CELSIUS can provide additional funding for pilot schemes, in order to make them financially viable. This can be mutually beneficial since both the company and the public sector are able to gain experience and knowledge which can be used for future projects.

5.1.7. Crowdfunding

Crowdfunding is a process in which some project is funded with a large number of small contributions, typically through specialist websites. The popularity of crowdfunding has grown a great deal in recent years with an estimated twelvefold increase globally between 2012 and 2015 [64]. Crowdfunding generally falls into the following four categories:

5.1.7.1. Rewards Based

In rewards based crowdfunding, contributors receive some form of reward in return for their contribution. Typically, this involves small contributions of money in return for some item, often a version of the product being crowdfunded. The size of the reward is often dependent on the amount contributed. Major rewards based crowdfunding platforms include Kickstarter and Indiegogo, which both allow the starter of a project to offer some product in exchange for contributions.

5.1.7.2. Donation Based

In donation based crowdfunding, contributors don’t typically receive any monetary or material reward [65]. Instead, the cause being funded is usually charitable or is related to some political cause. The reward can therefore be considered to be the feeling of having contributed to something with a value to society. Major players in donation based crowdfunding include GoFundMe, YouCaring and GiveForward.

5.1.7.3. Equity Based

Equity based crowdfunding is a more traditional version of funding in which the contributor receives shares in a company in exchange for, and proportionally to, their investment. The difference between equity crowdfunding and traditional investing, however, is that the former is typically open to a wider range of investors because the minimum amount required to invest tends to be lower. Crowdfunding platforms have also made the process easier to understand and easier to track investments. The Crowdfunding platform Indiegogo allows recipients to offer equity in exchange for contributions. Crowdcube is an example of a specialist investment based crowdfunding platform.
5.1.7.4. Lending Based

In lending based (or debt-based) crowdfunding (also known as peer to peer lending), contributions take the form of a loan which is to be repaid at a pre-agreed interest rate. The benefit for the funder is that the interest rate is higher than would be expected to achieve from a bank or building society though, naturally, the risk is higher. Examples of lending based crowdfunding platforms are Funding Circle (business lending) and Zopa (lending to individuals).

5.1.7.5. Crowdfunding of Green Projects

There is some precedent for the crowdfunding of small environmental projects. Several specialist websites for crowdfunding of green projects have been set up. For example, Greencrowd is a Netherlands based website that allows users to invest in small green projects throughout the Netherlands in return for a fixed interest rate. Only projects proposed by organisations within the public interest are eligible for funding. Other examples of green crowdfunding platforms are the following:

1. Oneplanetcrowd - A Dutch crowdfunder of green projects offering opportunities to crowdfund green projects. The website offers opportunities for all four types of crowdfunding described above. The website takes a small percentage of each funder.
2. greenCrowd - greenCrowd is an Australian crowdfunder that arranges finance to support sustainable energy and waste water management projects

Large regular crowdfunders also feature green projects. Around 9.5 percent of projects presented on Kickstarter are believed to be ‘green’. Indiegogo also features a significant number of green projects. Given the extremely rapid growth of crowdfunding, it seems likely that large platforms such as these will eventually dominate the green crowdfunding market.

5.1.8. Impact Investing

Impact investments are investments that aim to make social and environmental impacts. The return is usually lower than might be achieved for other non-green projects with similar risk and, as such, can be considered to be a form of philanthropy. Impact investment is typically involved with larger investments than crowdfunding. Corporate responsibility has seen a great deal of growth in recent years with 85 percent of S and P 500 companies producing sustainability reports in 2017; up from 20 percent in 2011. Impact investing is a potential funding source for district heating schemes and, since the required rate of return tends to be lower than for non-green projects, this may make district heating schemes viable when, otherwise, they would not be. However, for district heating schemes to be accepted for impact investing, the environmental and social benefits would need to be clearly set out. An example of impact investing is the Energy Access Debt Fund which aims to provide access to energy in developing nations.

5.2. Ownership Models

In this section, we review and give examples of the most common ownership models of district heating systems. Under each heading, we list the pros and cons. Note that this topic will be returned to in deliverable 2.3 which focuses on business models and contracts and deliverable 2.4 which focuses on the same topics for the ReUseHeat demonstrators in particular.

5.2.1. Customer Owned Cooperatives

User owned cooperatives are non-profit operations owned by the customers that are common in countries such as Denmark, Sweden and Germany [66]. Around 340 are in operation in Denmark alone [67]. In Denmark, the Danish District Heating Association (a ReUseHeat partner) provides support for such schemes, whilst similar organisations exist in other countries in which cooperatives are in widespread operation. In Denmark, only owners of property (rather than tenants) can be members of a cooperative. Connection to the network is...
sometimes mandatory in order to reduce the risk of low uptake. Before such a project is approved, the socio-economic benefits must be usually be demonstrated. According to the Danish District Heating Association [68], the principals for a cooperative are

1. One member - one vote.
2. Membership is open and voluntary.
3. Little or no member capital is required.
4. Any surplus belongs to the members and in proportion to the turnover between the member and the cooperative.

Some of the advantages of customer owned cooperatives are:

1. Customers have a stake in the business and are engaged.
2. Decisions are made democratically and transparently.
3. Profits are distributed to members.
4. Cooperatives sometimes benefit from tax breaks.

whilst some of the disadvantages are:

1. The establishment of a cooperative can be risky, given the high capital costs involved.
2. Decision making can be slow.
3. Risk of reputational issues caused by other badly run cooperatives.

5.2.2. State Ownership

Under state ownership, an asset is owned entirely by the state, though the operation and construction may be the responsibility of private partners. publicly owned district heating systems can be found in a wide range of European countries. They are common, for example, in Hungary where the majority of district heating systems are publicly owned (see, for example [69]). Stadtwerke München, responsible for a large district heating network in Munich, Germany is also publicly owned [70] whilst public ownership is common in Sweden, Denmark and Austria [71].

Some advantages of state ownership are:

1. Public sector often able to tolerate longer periods than the private sector.
2. Governments can consider social/environmental benefits as well as financial profit.
3. publicly funded projects more likely to be eligible for grant funding.

Some disadvantages are:

1. Often less incentive for efficiency.
2. Decision making often slower.
3. May be less experience and knowhow than in the private sector.
4. Can be politically difficult. Vulnerable to changes in government etc.

5.2.3. Private Ownership

Privately owned systems are owned and operated entirely by the private sector. The proportion of the district heating sector represented by private enterprise is growing, partly due to a growing trend towards the privatisation of district heating systems in Europe [71]. Examples of privately owned systems can be found in Upsalla (Sweden) [72], Sweden, Berlin and Hamburg in Germany [73] among many others.

Some of the advantages of private ownership are:

1. Easier to raise capital via bank loans than the public sector.
2. Private sector often more skilled at managing risk.
3. Private sector is not generally affected by political pressures.
5. Private sector generally has more experience through previous projects.
Some disadvantages are:

1. A high return on investment is usually required.
2. Private sector not generally primarily concerned with social/environmental issues.

5.2.4. Public-Private Partnerships

Public-private partnerships (PPPs) are joint ventures between public and private sector entities, typically of a long-term nature. PPPs are commonly used to deliver large-scale infrastructure projects and are in widespread use around the world. By involving the private sector, projects can benefit from the know how and experience of private enterprise whilst removing some of the financial and technical risk in that project. PPPs typically involve the formation of a special company, called a special purpose vehicle (SPV). In energy projects, these are called Energy Service Companies (ESCOs) which are typically jointly owned by both public and private sector entities.

BS|Energy, a partner on the ReUseHeat project and constructor and operator of the Brunswick demonstrator, is an ESCO, jointly owned by the city of Brunswick (25 percent) and Veolia (75 percent), a private company. This demonstrator will utilise waste heat from a newly constructed data centre and provide heat to around 400 homes in a new development. This project is funded using existing funds from the company along with some additional funding supplied by the ReUseHeat project.

Advantages of PPPs include:

1. SPVs and ESCOs have limited liability in the event of bankruptcy.
2. Much of the risk can be transferred to the private sector who are often better placed to deal with that risk.
3. Private companies often have knowhow and experience not available to the public sector.

Disadvantages include:

1. PPPs have been criticised for providing private sector with too high a return and providing poor value to the public sector.
2. Frequent renegotiations can worsen the deal for the public sector.

5.3. Summary

The funding of district heating projects takes many forms, depending on the ownership structure, the source of finance, the size of the project and economic, environmental and social objectives. However, in a number of workshops, one particularly successful type of development stands out and can perhaps be seen as an archetype, particularly in relation to finance. It is worth mentioning also the conventional wisdom that financial institutions are often unwilling to invest unless some of the capital expenditure and construction has already taken place, for example, but most importantly, the pipe network itself.

We represent these recommendations in note form:

1. Any future possible financial institution should be involved with the project at any early stage, whether or not they are willing to pay for, for example, a feasibility study.
2. Local and national grants are exceptionally useful to kickstart projects.
3. Financial institutions consider that ownership or management by a city lessens the risk.
4. Financial institutions look favourably on experienced contractors, whether they be large or small. In the latter case, for example, the city might have a good relationship with local contractors, a relationship that would be considered favourably by a lender.
5. Contracts are at the centre of development. On the one hand, financial institutions will want contracts which contain firm guarantees, for example, of customer demand. On the other hand, banks themselves are increasingly aware of changing ownership patterns and energy scenarios which may affect the future of a project. It is to be hoped that a wider, joint understanding of projects will facilitate funding.
6. Special funds, whether green funds or city based energy funds, clearly have a bright future and should provide an environment in which a more flexible and varied approach to contracts can be developed. For
example, contracts covering the aggregation of a number of smaller projects. Financial institutions are familiar with spreading risk and therefore vehicles that allow this to happen should be attractive.

7. Ideally, the ownership structure should be such as to minimise the overall project risk and risk to the individual stakeholders. It is often said that this is best covered with a special purpose vehicle (SPV) or Energy Service Company (ESCo). In practice, however, ownership may change throughout the course of a project with heavy involvement of the city initially, and the whole project sold into the private sector after completion. Rather than recommending a single ownership scheme as being ideal, we feel it is better to understand the realities and complexity of ownership for actual projects. There are situations in which a single company may offer all necessary functions from construction all the way to operation. There are also schemes in which a city or city-based company may always retain control, borrowing from financial institutions at a favourable rate.
Bibliography


A. Appendix: Description of Demonstrators

A description of each of the ReUseHeat Demonstrators is given below. Note that the Bucharest demonstrator pulled out of the project and has been replaced by a project to recover heat from a Berlin metro station.

A.0.1. Brunswick: Waste heat recovery from a datacentre

In Brunswick, Germany, Veolia and its local subsidiary BS|ENERGY demonstrate the recovery of excess heat from a data centre. Excess heat from the data centre will be injected into a newly built low temperature district heating network (LTDH). The temperature level of the excess heat before injection is around $25^\circ C$ which will be raised to $70^\circ C$. By supplying energy for space heating and domestic hot water in a nearby housing and commercial area, the water is cooled down and returned after usage to the heat pump to be reheated. By extracting heat for the district heating network, the heat pump will also lower the temperature of the cold water cycle of the data centre. This reduces the need to cool the data centre, thus providing a saving in energy and therefore cost. In addition, by using a LTDH network (4th generation heat network), losses can be reduced compared to if an older system with higher supply temperatures were used. The efficiency of the heat pump can therefore be increased, as it is directly linked to the difference in temperature levels between the heat source (data centre) and the heat sink (heat network). Furthermore, the heat pump will use CO2 as a working fluid in order to ensure the system’s sustainability. This refrigerant will combine the lowest possible global warming potential (GWP) with non-toxicity and, in addition, is non-flammable. A substation connected to the pre-existing DHN network (high temperature network) will supply peak load and work as a backup system. The planned layout of the system is depicted in figure A.1.

![Figure A.1: Layout for Brunswick demonstrator](image)

The demonstrator is expected to produce 2,300 MWh/yr of thermal energy, and to recover 1,750 MWh/yr of waste heat from the data centre. The peak heat demand is estimated to be around 1.8 MW. 250 kW of excess...
heat will be recovered by a 330 kW heat pump. This can be translated into an overall primary energy saving of 1,284 MWh/yr. Given an emission factor for natural gas of 275 g-CO2/kWh and for electricity of 580 g-CO2/kWh, this is translated into a global GHG emission savings of 304 tonnes-CO2/year.

BS|ENERGY’s main tasks in the project are the conception, realisation and operation of a heat recovery plant using data centre excess heat and electricity as input energies for a low temperature district heating grid. Veolia is responsible for the coordination of the input from the international Veolia group in the project, and, in particular, for the operative work of BS|ENERGY. It provides expertise and knowhow from the group regarding district heating networks, reuse of excess heat and heat pumps.

A.0.2. Madrid: Waste heat recovery from a hospital

The Madrid demonstrator utilises excess heat from a hospital for use as in input to a district heating network. The chosen hospital is the Hospital Universitario La Paz, the largest hospital in Madrid. It is situated in the district of Fuencarral - El Pardo and is a public university hospital that offers a variety of medical services to Madrid citizens. The Hospital is connected to a local district heating network, supplying all the buildings with heating and cooling.

This demonstrator is based on heat recovery from a cooling production process. Cooling is vital for hospitals, for example in surgery rooms, so it is required throughout the year. Electric chillers are used for cooling purposes. These dissipate the excess heat either to an air, ground or water source. Usually, this heat is either “wasted” and released into the environment or, if recovered, normally only meets temperature demands for preheating domestic hot water. However, with a booster heat pump, this heat can be recovered and upgraded to a suitable temperature level that can be used for heating a building or in a district heating network, achieving significant primary energy savings and CO2 emissions reductions.

The demonstrator will recover low temperature heat from the cooling circuit of the water-water electric chillers. Currently, this heat is dissipated through the cooling towers. The booster heat pump will capture the heat from the outlet water of the chiller cooling circuit and upgrade it in order to supply it to the existing district heating system. By using the booster heat pump, the water from the chillers’ cooling circuit is cooled, minimising the usage of the cooling towers. The current and future situations are shown in figure A.2.

Figure A.2: Layout for Madrid demonstrator
A.0.3. Nice: Waste heat recovery from sewage

The Nice demonstrator will be located in the Grand Arenas development district located in Nice, France. Within this district, a waste heat recovery system is conceived as a low temperature district heating network sourcing waste heat energy at the outflow batch of a waste water treatment plant (Summer: 25 – 30°C/ Winter: 8 – 13°C). The water is then distributed to the buildings substations which are equipped with reversible heat pumps to provide the necessary heating, cooling and sanitary hot water to the end users (4.0 MW / 2.9 GWh heating, 2.5 MW / 3.5 GWh SHW, 5.1 MW / 4.5 GWh cooling).

Based on this system (not co-funded by the ReUseHeat project), the demonstration of an innovative district scale Local Energy Management dashboard will be put in place (co-funded by the ReUseHeat project). The dashboard will provide real time information about the energy and environmental performance of the system to the community by mapping all energy fluxes related to the district. It is expected to raise awareness of the deployed energy solutions to the local community and to end users. The dashboard will showcase its role and impact within the local energy mix, raise the active involvement in energy usage and, as a result of the monitoring, provide a positive feedback on the overall operation of the system. The proposed layout of the system is depicted in figure A.3.

![Figure A.3: Layout for Nice demonstrator](image)

A.0.4. Bucharest: Waste heat recovery from a metro station

The main objective of the Bucharest demonstrator is to extract excess heat from the ventilation system of a metro station in Bucharest, Romania and make use of it either by injecting it into the Bucharest district heating network or into a separate/private heat supply network. The conceptual representation of the demonstrator is presented in figure A.4.

Waste heat recovery will be performed by extracting heat from the subway platform area and converting it to hot water via a water to water heat pump. The heat source will integrate a fan coil unit network mounted at high level and, by extracting the waste heat, it will be possible to control and maintain a comfort temperature for the passengers and metro staff.

The waste heat sources are:

- Heat generated by electric motors due to their electrical and mechanical functioning at acceleration, at constant speed and at deceleration.
- Electric and mechanical brakes on trains.
- Station electrical equipment.
- Passengers.
Heat recovery will be realised with a water to water heat pump. The heat source collector will consist of a fan coil network of around 30 fan coil units. During the summer time, the temperature can exceed $27^\circ C$ and during the winter time it can exceed $15^\circ C$. The expected thermal power available is around 250kW.

The targeted end-use heating demand is the local district heating network (DHN) or the Municipal District Heating Network, preheating domestic hot water. The heat recovery will be realised with a water to water heat pump. The hot water supplied by the heat pump will pre-heat the domestic hot water through a plate heat exchanger. The supply temperature by the heat pump will be $55^\circ C$. The expected thermal power to be provided is 300kW. The demo case will be implemented into an existing metro station, on the source side, and for the demand side, thermal energy will be supplied to an existing DHN.

The DHN substation can supply hot water for heating, during the winter time, and domestic hot water for the residential area, but also for public buildings, depending on their proximity. For the metro stations, Metrorex - the metro system operator - keeps track of the temperatures and relative humidity of the air, providing monthly average values for every station in Bucharest. On the demand side, being a DHN substation monitoring every single parameter it’s a must-have for proper management and control.
B. Appendix: UK National Grid Scenarios

The UK National Grid defines energy scenarios on a yearly basis for use in government policy and for other energy planning [74]. Previous to 2018, the scenarios were based on different levels of economic growth and government effort to decarbonise. In 2018, a different approach was taken in which each scenario was defined with different assumptions about the level of decentralisation and the speed of decarbonisation. Each of the four scenarios is summarised below:

B.1. Community Renewables

Under this scenario, a relatively high level of decentralisation is assumed. The UK government’s commitment to reduce carbon emissions by eighty percent by 2050 is met. There is extensive use of smart technology to manage peak loads and energy efficiency improves such that EU targets are met. The government succeeds in its target to end all sales of petrol and diesel powered cars and electrical vehicles become the most popular form of private transportation. For heavy goods vehicles, significant progress is made towards replacing natural gas with hydrogen. Significant changes regarding the heating homes have been made and heat pumps are the dominant technology. There is also a significant role for district heating. Electricity supply is dominated by solar and wind power, combined with efficient storage. Gas is still important in the short to medium term but is eventually largely replaced with green gas.

B.2. Two Degrees

The Two Degrees scenario meets the UK government’s targets of reducing the carbon emissions by 80 percent by switching to larger and more centralised technologies. Under this scenario, electricity demand is greatly reduced due to hydrogen heating. Electrical appliances are generally much more energy efficient. Electric vehicles become the most popular mode of private transport whilst demand for public transport also grows. Hydrogen powered commercial vehicles, replacing natural gas powered vehicles, also become more widespread. A large effort is made to improve the thermal efficiency of homes whilst the dominant heat sources are gas boilers, district heating and heat pumps. Energy generation, primarily from wind and nuclear, is based on the transmission network itself, improving efficiency. North Sea gas still plays an important role and some green gas is available.

B.3. Steady Progression

Under this scenario, the government’s 2050 decarbonisation target is not met but steady progress is made. Improvements in the energy efficiency of appliances and the electrification of heat is slower than under the Community Renewables and Two Degrees scenarios but there is a large increase in the number of electric vehicles, giving an important role to smart technology in managing peak demand. Gas powered vehicles continue to play an important role in the commercial sector. Most homes still rely on the use of gas boilers and there is little improvement in energy efficiency or the use of heat pumps. Electricity is generally generated on a large scale, rather than locally but there is development of nuclear power and offshore wind. Gas still plays an important role with shale gas providing the majority of the supply.

B.4. Consumer Evolution

Under this scenario, some progress is made towards the government’s target of reducing carbon emissions by eighty percent by 2050. There are some improvements in energy efficiency and electric vehicles become the
dominant choice of private transport. Local communities, businesses and homes are incentivised towards local generation. Limited progress is made towards the decarbonisation of heat with small improvements in thermal efficiency and some progress towards the rollout of heat pumps. Electricity generation is focused on small scale renewables and nuclear power. Gas continues to be in widespread use but, by 2050, shale gas is the largest source of supply.
C. Appendix: Paper on Cognitive Bias
Probability distortion, with applications to investment bias

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Abstract

Cognitive bias is thought to play an important role in cost and time overrun in infrastructure projects. It is common for project appraisers to make overly optimistic assessments of project assumptions which, in turn, leads to unrealistic assessments of time and cost. These sorts of appraisals are usually made using simple models that take both technical and economic factors into account. Often, there is some uncertainty in one or more model inputs and these uncertain inputs are represented with probability distributions which are propagated through the model to assess the impact on the output. Cognitive bias, however, can lead to overly optimistic assessments of input distributions, which feeds through to model output, giving an overly optimistic assessment of important indicators. In this paper, methodologies for distorting probability distributions are introduced with the intended purpose of debiasing. These distortions are then demonstrated using a simple spreadsheet model of a hypothetical district heating project.

1 Introduction

The body of theory related to the distortion or weighting of distributions that arises from the idea of cognitive bias can loosely be described as Prospect

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Theory. Prospect Theory is now part of what is called behavioural economics, which investigates the idea that we do not necessarily obey the strict rules of classical utility but may be influenced by other thoughts and feelings, manifest as our behaviour. Kahnemann and Tversky list ways in which we can be biased away from what might be a rational choice [12].

The idea here is to provide simple families of bias distortions which may be tested out in situations where judgements are made about inputs to models on which CAPEX or OPEX investments are to be made. The authors are fortunate to work in a European project (see acknowledgements) which has an interest in these ideas. Background models for such investments often take the form of some kind of dynamic spread sheet. In the spirit of modern sensitivity analysis, we are able to propagate bias on inputs to outputs in simple, but carefully designed, computer experiments.

Infrastructure projects are widely acknowledged to be heavily influenced by cognitive bias, which can cause cost and time overruns. Several notable examples of overruns can be found in the United Kingdom. The final cost of the Scottish parliament building in Edinburgh, completed in 2004, was £430m and took five years to build after initial cost estimates were set at around £40m with an estimated construction time of two years [21]. A more recent example is the Crossrail project in London which, at the time of writing, is expected to open nine months after its original schedule and run several hundred million pounds over budget [1]. Other notorious examples of time and cost overrun globally include Berlin Brandenburg airport (at least six years behind schedule and six times the initial cost [4]), Sydney Opera House (over spent of 14 times the original estimated cost) and the Olympic games which have seen an average cost overrun of 179 percent between 1960 and 2012 [9]. It is estimated that 30 to 60 percent of UK infrastructure projects overrun in cost in the 1990s [11].

The exact causes of cost and time overrun have been the subject of a large body of research. It has been claimed that overrun can result from both deliberate and non-deliberate factors. In the former case, evidence is presented by [8] that overrun can result from deliberate efforts by bidders to underestimate the costs of a project during the bidding process, in order to increase their chances of winning the contract.

One of the biggest root causes of cost and time overrun is believed to be optimism bias [5]. Optimism bias is the systematic tendency for humans to be overly optimistic about the likelihood and/or impact of some event. It manifests itself in the planning and construction of infrastructure projects
causing project appraisers to be overly optimistic in their assumptions which, in turn, leads to overly optimistic assessments of the revenue, costs and construction time. Flyvberg et al argue that a more accurate description for ‘cost overrun’ is in fact ‘cost underestimation’ [6].

A number of approaches have been proposed for dealing with optimism bias in infrastructure projects. One approach is simply to make a better attempt at identifying risk and estimating costs, revenues and construction times. Numerous techniques have been suggested including delegitimising overoptimistic budgeting, fiscal incentives for accurate budgeting and the use of independent project appraisers [7]. In Reference Class Forecasting (RCF), the overall cost of a project is adjusted according to experience from other similar past projects. The UK Treasury’s Green Book makes use of RCF by making recommendations regarding an additional percentage to be added to the calculated costs of a project [17]. The percentages depend on the type of project and are calculated on the basis of the results of a report in which the cost overrun of a large number of projects was assessed [15].

This paper was motivated by the need to develop practical tools with which to investigate the effects of cognitive bias, particularly in capital projects. The most sophisticated methods use techno-economic models in which technical modelling, often in the form of engineering simulation, is married to economic models with inputs such as costs, discount rates associated with debt, demand, cash flow and so on. Questions of risk and uncertainty increasingly dominate deterministic modelling [2]. Cognitive bias has had a somewhat separate history of research within behavioural economics, but the economic thinking is now fusing through to affect the private and public sectors and practical methods are sometimes given the label debiasing [10].

The standard approach in risk management is to investigate the effect of random inputs on different outputs such as cost, as a way of capturing uncertainty. Risk metrics attached to the outputs may be means, medians, standard deviations and so on. In financial economics we have Value-at-Risk (VAR), Mean Value-at-Risk and a developing raft of other metrics [3].

2 Bias as distortion of distributions

We consider cognitive bias to be represented by an upward or downward distortion of a distribution. The literature on such distortions falls into
different groups characterised by a direct transformation of the cumulative distribution function (cdf) $F(x)$ of a random variable $X$ or of its quantile function $F^{-1}(\alpha)$. Good intuition is provided by work on income distribution: $F(x)$ describes the actual incomes, whereas $F^{-1}$ describes a person’s position in the income distribution. Very broadly, the first is of interest in mainstream economics and the second in welfare economics. It is important to note that, in statistical theory, changes in the distribution of a random variable are often achieved by a transformation of the variable itself which will, for example, induce a change on the quantile function.

**Definition 2.1.** A distortion of a random variable $X_1$ with cdf $F_1(x)$ is a new random variable $X_2$ with cdf $F_2(x) = v(F_1(x))$ where $v(x)$ is a non-decreasing function $v(x) : [0, 1] \rightarrow [0, 1]$ with $v(0) = 0$ and $v(1) = 1$.

Note that, where the meaning is clear, we shall sometimes refer to the function $v(x)$ itself as the distortion. In this paper, we will be interested particularly in convex and concave distortions. We note also that such functions are assumed to be suitably measurable.

**Definition 2.2.** A convex (concave) distortion of a random variable $X_1$ with cdf $F_1(x)$ is a new random variable $X_2$ with cdf $F_2(x) = v(F_1(x))$ where $v(x)$ is a convex (concave) increasing function $v(x) : [0, 1] \rightarrow [0, 1]$ with $v(0) = 0$ and $v(1) = 1$.

Note that we use the stronger “increasing” rather than non-decreasing to make proofs a little easier.

**Definition 2.3.** For convex (concave) distortions $v_1(x)$ and $v_2(x)$, applied to a cdf $F(x)$, we say that $v_2(x)$ is stronger than $v_1(x)$ if there is a convex (concave) increasing and differentiable function $\phi(x) : [0, 1] \rightarrow [0, 1]$, such that $v_2(x) = \phi(v_1(x))$ for $x \in [0, 1]$.

The following lemma describes a condition on the densities equivalent to the “strength” condition, above. Throughout, $v’, v”\ldots$ refer to differentials, which are assumed to exist, when necessary.

**Lemma 2.4.** For two distortion functions $v_1(x), v_2(x)$ with $v_2(x) = \phi(v_1(x))$, for some convex distortion $\phi$, $v_2$ is stronger than $v_1$ if and only if

$$\frac{v_2''(x)}{v_2'(x)} \leq \frac{v_1''(x)}{v_1'(x)}$$

for all $x \in (0, 1)$. 

Proof. We compute:

\[
\frac{v''_2}{v'_2} = \frac{\phi'' v'^2_1}{\phi'} + \frac{v''_1}{v'_1}
\]

The result follows because the required condition is determined by the sign of \(\phi''\) for all \(x \in [0, 1]\) and the first differentials in the numerators are nonzero on \((0, 1)\).

The case in which \(v_1(x) = x\), the identity, and \(F_1(x)\) is a base distribution implies that \(v_2 = \phi(x)\) so that \(F_2(x) = \phi(F_1(x))\) is a distortion of the base distribution. This is the main case which will concern us in the paper. That is to say, we consider the biasing distortion applied to some base case.

Lemma 2.5. A convex distortion \(v_2\) of the cdf \(F(x)\) for a random variable defined on \([a, b]\) is stronger than a convex distortion \(v_1\) if and only if, for the resulting pdfs

\[
\frac{d}{dx} \{\log(f_2(x))\} > \frac{d}{dx} \{\log(f_1(x))\}
\]

for all \(x \in (a, b)\).

Proof. Let \(F_2(x) = v(F_1(x))\) be a strictly convex distortion of the cdf \(F_1(x)\). Differentiation gives \(f_2 = v'(F_1)f_1\) and

\[
\log(f_2) = \log(v'(F_1)) + \log(f_1).
\]

Differentiating again and rearranging gives:

\[
\frac{v''(F_2(x))}{v'(F_1(x))} = \left(\log(f_2(x)) - \frac{f_2(x)}{f_1(x)}\right) \frac{1}{f_1(x)}
\]

Comparing the left hand side for \(v_1\) and \(v_2\) we see that the result holds, after cancellation of terms involving \(f(x)\) and using Lemma 2.4.

2.1 Stochastic orderings

We can consider the inequality in Lemma 2.5 as defining a stochastic ordering between two distributions with pdfs \(f_1(x)\) and \(f_2(x)\) and write \(f_1(x) \prec f_2(x)\). We may also write \(F_1(x) \prec F_2(x)\) for the cdfs or \(X_1 \prec X_2\) for the corresponding random variables. In fact, this is a well-known ordering, usually called the Likelihood Ratio (LR) ordering. The following Lemma collects two of the important equivalent conditions given by [14] (see also [16]);
Lemma 2.6. The inequality in Lemma 2.5 is equivalent to each of the following two conditions:

(i) \( \frac{f_2(x)}{f_1(x)} \) is increasing in \( x \)

(ii) \( v(x) = F_2(F_1^{-1}(\alpha)) \) is convex (increasing) for \( 0 \leq \alpha \leq 1 \).

We omit the proof which is straightforward and is given in [14].

A consequence of the strict version of the ordering \( f_1(x) \prec f_2(x) \), which we have adopted, is that \( f_1(x) \) and \( f_2(x) \) cross exactly once at the special point \( x^* \). This is related to the locus \( (\alpha, \beta) = (F_1(x), F_2(x)) \). We easily compute:

\[
\frac{d\beta}{d\alpha} = \frac{f_2(F_1^{-1}(\alpha))}{f_1(F_1^{-1}(\alpha))}.
\]

Thus we have that \( \alpha^* = F_1(x^*) \) is the \( \alpha \)-value at which \( \frac{d\beta}{d\alpha} = 1 \). Equivalently, writing \( F_2(x) = v(F_1(x)) \) for convex increasing \( v(x) \), \( x^* \) is the solution of \( v'(x) = 1 \).

In the study of stochastic orderings, one often seeks the class \( U \) of order preserving (also called invariant) functionals \( u \) on the pdf such that

\[
F_1 \prec F_2 \iff u(f_1) \leq u(f_2), \text{ for all } u \in U.
\]

The important linear case is when

\[
F_1 \prec F_2 \iff E_{X_1}\{u(X_1)\} \leq E_{X_2}\{u(X_2)\}, \text{ for all } u \in U.
\]

Although, ("unfortunately" as Lehmann and Rojo say) our (MLR) ordering is not linear, in the above sense, we are able to prove the following logarithmic version.

Integration by parts gives, for a utility function \( u(x) \), and density \( f(x) \):

\[
\int_a^b u(x) \log f(t) dt = \left[ U((x) \log f(x)) \right]_a^b - \int_a^b U(t) \frac{d}{dt} \log f(t) dt, \tag{2}
\]

where \( U(x) = \int_a^x u(t) dt \). Using inequality 2, we can easily establish the following.

Lemma 2.7. For two density functions \( f_1 \prec f_2 \) defined on an interval \([a, b]\)

\[
\int_a^b u(x) \log f_1(t) dt \leq \int_a^b u(x) \log f_2(t) dt
\]
for all utility functions \( u(x) \) such that
\[
U(b) \log f_1(b) - U(a) \log f_1(a) = U(b) \log f_2(b) - U(a) \log f_2(a) = 0
\]
and \( U(x) = \int_a^x u(t) dt > 0, \ t \in (a,b) \).

A rich class of utilities which satisfy the conditions in Lemma 2.7 is to take
\( u(x) = u_1(x) - u_2(x) \) where \( u_1(x) \) and \( u_2(x) \) are the pdfs of two random variables with cdfs \( U_1(x) \) and \( U_2(x) \) respectively such that \( U_1(x) > U_2(x) \) for \( x \in (a,b) \). Namely the second random variable first order stochastically dominates the first, in a strong sense.

2.2 Prospect and Arrow-Pratt theories

There is a close relationship between the probability distortion defined here and Prospect Theory. In that theory, two kinds of distortion are considered: of the probability and of the utility function \( u(x) \); the latter under the heading of risk aversion. Thus, let \( x \) be some base value, typically money, and let \( u(x) \) be a subjective appreciation of that value. It is of considerable interest to us that the Arrow-Pratt measure of risk aversion is
\[
-\frac{u''(x)}{u'(x)}.
\]

For two different utility functions \( u_1(x) \) and \( u_2(x) \), a subject “owning” \( u_2(x) \) is at least as risk averse as the owner of \( u_1(x) \) if
\[
-\frac{u''_1(x)}{u'_1(x)} \leq -\frac{u''_2(x)}{u'_2(x)}.
\]

Except for a sign change, these conditions are the same as in Lemma 2.4, which were applied to densities \( f_1(x) \) and \( f_2(x) \). The analogous results hold.

In fact, the link to convexity in the condition that \( F_2(x) = v(F_1(x)) \) for convex increasing \( v(x) \) is exactly the Arrow-Pratt risk aversion applied to densities. In the case that \( u(x) = x \), the base case, we see that \( u''(x) \leq 0 \), giving convexity of \( u(x) \), and absolute risk aversion. Another consequence is that the utility functions \( u_1(x) \) and \( u_2(x) \) cross exactly once.

Prospect theory goes one step further in two respects. It not only considers both risk aversion and probability distortion, but carefully distinguishes
concave cases above a particular reference point and convex below (or vice-versa). This is stronger than the simple crossing of utilities or probability densities exhibited here. Using the analogue of utility risk aversion for probabilities has been addressed by a number of authors and is often called “probability risk aversion”. See, for example, [18, 22, 23].

3 Parametric families

In all of these cases, we will use the results of Lemma 2.5 to see how the conditions are transferred to conditions for the ordering $\prec$ on the parameter(s) of the family.

Normal (Gaussian)

Taking logarithms of $N(\mu, \sigma^2)$, $f(x)$ we have

$$\frac{d}{dx} \log(f(x)) = \frac{2(x - \mu)}{\sigma^2}$$

The condition for $f_1(x) \prec f_2(x)$ is that $N(\mu_2, \sigma_2^2)$ is a distorted version of $N(\mu_1, \sigma_1^2)$ if and only if $\sigma_1 = \sigma_2$ and $\mu_2 \geq \mu_1$.

General exponential family

The Gaussian case is a special case of the more general exponential family

$$f(x, \theta) = e^{\theta t(x) - K(\theta)} f_0(x),$$

where $K(\theta)$ is the cumulant generating function of the base density $f_0(x)$ and $t(x)$ is the sufficient statistic. Then

$$\frac{d}{dx} \log(f(x)) = \theta t'(x) - \frac{f_0(x)}{f_0(x)}.$$ Under the condition that $t'(x)$ has constant sign (which we can take as positive) the required condition is that, for two distributions in the family with parameters $\theta_1$ and $\theta_2$, we see that the required condition is $\theta_2 \geq \theta_1$.

Beta Distribution

The pdf of a Beta distribution is defined by

$$f(x) = x^{\alpha-1}(1 - x)^{\beta-1} B(\alpha, \beta), \quad x \in [0, 1],$$
where $\alpha > 0$ and $\beta > 0$ are parameters and $B(\alpha, \beta)$ is the Beta function. The condition for two Beta random variables $X_1, X_2$ with parameters $(\alpha_1, \beta_1)$ and $(\alpha_2, \beta_2)$, respectively, when $X_2$ is a convex distortion of $X_1$, is

$$\{\alpha_1 \geq \alpha_2\} \cap \{\beta_1 \leq \beta_2\}.$$

**Gamma Distribution**

The pdf of a Gamma distribution is

$$f(x) = \frac{1}{\Gamma(k)} \theta^k x^{k-1} e^{-\theta x}, \quad x > 0,$$

with parameters $k, \theta > 0$. The condition is:

$$\{k_1 \geq k_2, \; \theta_1 \leq \theta_2\}.$$

**Pareto Distribution**

The pdf of a Pareto distribution is defined by

$$f(x) = ab \frac{a}{x^{a+1}}, \quad x > 0,$$

and parameter: $a > 0$. The parameter $b$ does not affect the ordering and the condition is $a_2 < a_1$.

**Weibull Distribution**

The pdf of the Pareto distribution is

$$f(x) = \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}.$$

with parameters $k, \lambda > 0$. The condition is

$$\{k_1 = k_2, \; \lambda_1 > \lambda_2\}.$$

**Generalised Extreme Value (GEV) distribution**

The basic one parameter density is

$$f(x, \xi) = \frac{1}{\xi} \left(1 + \frac{x}{\xi}\right)^{-\frac{1}{\xi} - 1} \exp \left(\frac{1}{\xi} \left(1 + \frac{x}{\xi}\right)^{-\frac{1}{\xi}}\right).$$

Analysis shows that for no two different $\xi$ values can we write $f_1(x) \prec f_2(x)$. That is to say the distributions are incomparable by the ordering.
3.1 Family preserving transformations

If \( F(x, \theta) \) represents a family of distributions, parameterised by a parameter \( \theta \), then we can consider more generally when a distortion \( v(x) \) keeps the new cdf in the same family. We write this as \( F(x, \theta_2) = v(F(x, \theta_1)) \). Assuming the inverses exist and setting \( F(x, \theta_1) = y \), we have the condition

\[
v(y) = F(F(y, \theta_2)^{-1}, \theta_2)
\]

We note the relationship to (ii) in Lemma 2.6. As an example, consider the exponential distribution with pdf \( f(x, \theta) = \theta e^{-\theta x} \) and cdf \( F = 1 - e^{-\theta x} \). Then

\[
v(x) = 1 - (1 - y)^{\frac{\theta_2}{\theta_1}}.
\]  

(6)

It is clear that, since the mean of the distribution is \( \frac{1}{\theta} \), increasing the mean is a convex distortion. This is confirmed by \( v(x) \) being convex or concave depending on whether \( \theta_2 \leq \theta_1 \) or \( \theta_1 \leq \theta_2 \). We can compute the function \( v(x) \) similarly for any of the distributions in the last section.

3.2 A class of distortion functions

We seek a simple one parameter class which can potentially be used for any distribution to express bias. For a parametric family, such a distortion will typically lead to a new distribution that is no longer in the family.

Möbius functions take the form

\[
g(x) = \frac{a + bx}{c + dx}
\]

where \( a, b, c \) and \( d \) are parameters satisfying \( ad \neq bc \). The unique version satisfying \( g(0) = 0 \) and \( g(1) = 1 \) is:

\[
v(x, t) = \frac{tx}{1 + (t - 1)x}
\]  

(7)

which is convex for \( 0 < t \leq 1 \) and concave for \( t \geq 1 \).

The function \( v(x, t) \) has some attractive features. It represents a subgroup of the group of all Möbius functions with identity at \( t = 1 \) when \( v(x) = x \) and with inverse \( v(x, t)^{-1} = v(x, \frac{1}{t}) \). At the special points at which \( t^2 + t - 1 = 0 \), whose solutions are \( \lambda \) and \( 1 - \lambda \), where \( \lambda = \frac{\sqrt{5} - 1}{2} \), the ubiquitous Golden Section, we have

\[
v(v(x, \lambda), \lambda) = v(x, 1 - \lambda).
\]
It is interesting to consider \( v(x, t) \) itself to be the cdf of a family of distribution functions with parameter \( t \). In that case, the family preserving distortions lie in the same class. If \( v(y) \) is defined as equation 7 with \( \theta \) replaced by \( t \) we have the symmetry
\[
v(y) = v(y, t_2 t_1^{-1}).
\]
Another important class of distributions preserved under \( v(x, t) \) in equation 7 is the generalised logistic class \( f(t) = \frac{1}{1 + e^{x-\mu}} \). A separate paper will cover this special case in more detail [20].

### 3.3 Standardising Distortions

Sensitivity analysis assesses the effect of model input uncertainty on model output. This is done by assigning some probability distribution to each model input, taking random draws from that distribution and propagating it through the model to assess the impact on the output. There are often good reasons to represent different model inputs with different families of probability distributions. For example, if the input is an efficiency parameter, it will typically be constrained between zero and one and might be modelled using a Beta distribution. Electricity tariffs, on the other hand, are often modelled using a lognormal distribution [19]. In this paper, standardised distortions have been defined such that they can be applied to any probability distribution. An issue so far not discussed, however, is how to define some standardised size of a distortion for any probability distribution such that comparable distortions can be made, regardless of the family, or properties, of the distributions. A simple approach is described below and is used in the experiments in the next section.

**Median Based Standardisation**

A median based distortion of a distribution maps the \( \frac{1}{2} + \delta \) quantile of the baseline distribution to the median of the distorted distribution where \( \delta \) is a number to be selected between \(-\frac{1}{2}\) and \(\frac{1}{2}\).

**Signed Area**

When we have an empirical, non-standard distribution we can use a distortion such as that suggested in subsection 3.2. This suggests using some aspect of \( v(\alpha) = F_2(F_1^{-1}(\alpha)) \) as a measure of dispersion which can then be used to standardise. When \( v(x) \) is convex/concave, as in our theory, it is natural to
take the signed area between the line $\beta = \alpha$ and $v(\alpha)$:

$$A(F_1, F_2) = \frac{1}{2} - \int_0^1 F_2(F_1^{-1}(\alpha))d\alpha.$$ 

In the exponential case in 6, we have

$$A_v = \frac{1}{2} \frac{\theta_2 - \theta_1}{\theta_1 + \theta_2} = \frac{R - 1}{R + 1},$$

where $R = \frac{\theta_2}{\theta_1}$. This is scale invariant, emphasising its potential as a standardised measure of shift. When we use the special distortion $v(x,t)$ in equation 7, we have

$$A(F_1, F_2) = \frac{1}{2} - \int_0^1 v(x,t)dx = \frac{2t \log(t) + 1 - t^2}{2(t - 1)^2} = \frac{1 - t}{6} + 0((1 - t)^2).$$

Note that the signed area is positive when $0 \leq t \leq 1$ and negative when $t > 1$.

4 Applications

In this section, we present the results of a simple experiment aimed at demonstrating the use of distortions in the context of sensitivity analysis in energy modelling. The experiment is performed using a simple spreadsheet model, incorporating both technical and economic elements, for assessing the financial viability of a district heating scheme. Whilst the modelling itself is based upon a hypothetical district heating scheme, the model parameters and performance characteristics (KPIs) are, for realism, based on the authors’ experiences on the ReUseHeat project in which four district heating demonstrator projects are partners.

4.1 District Heating

District heating is a system in which heat is generated in a centralised location and distributed through a network of insulated pipes, typically through heated water. Commonly, excess heat from a nearby source such as a factory is pumped into the network thus ‘reusing’ that heat and providing an
environmentally friendly alternative to non-renewable sources. Heat is typically transferred using an electric heat pump, a device that transfers heat from some heat source to a heat ‘sink’. Crucially, given some excess heat, the number of units of heat pumped to the heat sink is usually higher than the units of electricity used to power the heat pump. The ratio of these two quantities is called the coefficient of performance (COP) which, since electric heating is 100 percent efficient, can be interpreted as the ratio of heat delivered by the heat pump to the amount that could be produced by generation from electricity. If the COP is greater than one, energy savings can be made by pumping heat rather than by generating it.

4.2 A simple model: district heating

We define a simple techno-economic spreadsheet model designed to assess the financial viability of a heat pump based district heating scheme. The outputs of the model are the estimated net present value (NPV) and the internal rate of return (IRR) of the project based on the model inputs. The model is based on a model presented in [13].

Let the lifetime of a project be $N$ years. Additionally, let $I_t$ and $M_t$ represent the investment costs and maintenance costs of the project respectively in year $t$. Define $F_t$ to be the total cost of the electricity required to power the heat pump in year $t$ and let $r$ be the discount rate, which is assumed to be constant over the lifetime of the project. The total costs in year $t$ are therefore given by

$$C_t = I_t + M_t + F_t. \quad (8)$$

The total cost of electricity $F_t$ depends both on the units of electricity required such that the heat demand $H_t$ is met, and the cost per unit of electricity $Q$. The number of units of electricity required depends on the Coefficient of Performance (COP). The total cost of electricity to run the heat pump in year $t$ is

$$F_t = Q \frac{H_t}{P}$$

where $P$ is the actual coefficient of performance of the heat pump.

The revenue from the project depends both on the number of units and the price per unit sold. Let $T$ be the cost per unit of heat to the end user in € per kw/h. The revenue from heat demand in year $t$ is therefore given by

$$R_t = H_t T. \quad (9)$$
The net present value of the project can be calculated by estimating the difference in the present value of all revenues and all costs summed over all years:

\[
NPV = \sum_{t=1}^{N} \frac{R_t - C_t}{(1 + r)^t},
\]

whilst the internal rate of return (IRR) is calculated by setting the NPV to zero and solving for \( r \). The model variables and their units are summarised in table 1.

4.3 Experiments

In this experiment, we demonstrate the use of distortions on the inputs to the model defined above. Sensitivity analysis is performed on a one-at-a-time basis by propagating draws from each input distribution through to the model output. For different model inputs, both a baseline distribution and a distorted version are defined. The distribution of the model output is compared in each case.

The model produces as outputs the net present value (NPV) and the internal rate of return (IRR) of a district heating project. In any modelling exercise, the values of each model input have to be defined. In this example, we treat some model inputs as fixed and others as probability distributions, in order to represent inherent uncertainty. The effect of distorting each input distribution on a one-at-a-time basis is demonstrated by comparing the model output. Those model inputs that are kept constant are listed in table 2 along with their assigned values.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_t )</td>
<td>investment costs in year</td>
<td>€</td>
</tr>
<tr>
<td>( M_t )</td>
<td>maintenance costs in year ( t )</td>
<td>€</td>
</tr>
<tr>
<td>( H_t )</td>
<td>Heat delivered to the end user in year ( t )</td>
<td>kw/h</td>
</tr>
<tr>
<td>( r )</td>
<td>discount rate</td>
<td>-</td>
</tr>
<tr>
<td>( P )</td>
<td>coefficient of performance of the heat pump</td>
<td>-</td>
</tr>
<tr>
<td>( T )</td>
<td>tariff per kw/h of heat sold to the end user</td>
<td>€</td>
</tr>
<tr>
<td>( Q )</td>
<td>cost of electricity per kw/h</td>
<td>€/kw/h</td>
</tr>
<tr>
<td>( N )</td>
<td>lifetime of the asset</td>
<td>years</td>
</tr>
</tbody>
</table>

Table 1: Table of variables
This leaves the coefficient of performance \( P \), the electricity price \( Q \) and the discount rate \( r \) which are all represented with probability distributions. The baseline distribution in each case is defined to be the distribution of the input before distortion has taken place. The aim of the experiment is then to assess the impact of distorting each of these distributions. The baseline distributions of the model inputs are defined as

\[
P \sim LN(-9, 0.1^2), \quad Q \sim N(3.7, 0.05^2), \quad r \sim N(0.05, 0.01^2).
\]

We use the median shift approach defined in section 3.3 to standardise the level of distortion placed on the model inputs. Here, for illustration, we choose values of \( \delta = 0.05 \) and \( \delta = -0.05 \) respectively to yield two examples of distorted distributions of the NPV formed by distorting the COP \( P \). The effect is that, in the former case, the mean of the distribution is shifted from \( \mu_C = 3.7 \) to \( \mu_C = 3.763 \) and, in the latter case, to \( \mu_C = 3.637 \). One way of illustrating the effect of distortions on the output distributions is to plot the cdf of one against the other with each point on the line representing a different quantile. The distortions of the NPV cdfs from an upward (red) and downward (blue) shift in the mean are shown in Figure 1 in which each one is plotted against the baseline NPV cdf.

The impact of distorting each of the input distributions is now demonstrated further. The analysis is done on a one-at-a-time basis such that, in each case, each of the other inputs defined by probability distributions are now treated as constants (the values are set to the mean of the defined baseline distribution). In the simulation, 256 Random values of \( \delta \) are drawn from a uniform distribution \( U(-\frac{1}{2}, \frac{1}{2}) \) and used to distort the input distribution such that there are 256 distortions in total. For each one, 512 random draws are taken from the distorted distribution and used as inputs to the model. These are used to calculate quantiles of the output distribution in each case. The mean of the input distribution is then plotted against different quantiles of the output distributions. Quantile regression is used to map the size of the probability distortion to the quantiles of the output distribution. This was done using the \textit{fitlm} function in Matlab 8.5.0. The results are shown in

<table>
<thead>
<tr>
<th>( N )</th>
<th>( T )</th>
<th>( I_1 )</th>
<th>( I_2, \ldots, I_{10} )</th>
<th>( M_1 )</th>
<th>( M_2, \ldots, M_{10} )</th>
<th>( H_1, \ldots, H_{10} )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.00007</td>
<td>406</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>1,750,000</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 2: Table of model values
Figure 1: Distorted against non-distorted CDFs for upwards (red) and downwards (blue) shift in the distribution of the COP.

Figure 2 in which the mean of the distribution placed on the inverse of the COP $\frac{1}{x}$ is plotted against each quantile of the distribution of the NPV (top) and IRR (bottom). The line of best fit from the linear regression on each quantile is also shown. Here, the effect of distorting the distribution becomes clear. As the mean of the distribution of the COP is reduced (i.e. we move to the right on the graph), the entire distributions of both the NPV and IRR shift downwards. In addition, the distribution becomes wider, implying additional uncertainty. Whilst, in the lower case, it is clear that the linear regression approach could be improved upon, we do not attempt to do this; rather we suggest that other approaches are available and should be used when appropriate.

Similar results are shown in Figure 2 for distortions of the distribution of the electricity price. As the mean of the distribution of the electricity price is increased, the entire distributions of the NPV and IRR shift downwards, indicating that the probability of the project being unprofitable is increased. Similarly to the results from distorting the distribution of the COP, the distribution becomes wider as the distortion is increased. This would mean
that optimism bias in both the electricity price and the COP would result in an underestimation of the location of the entire distribution as well as an underestimation of its dispersion.

For completeness, we now compare the effect of using two types of distortion on a model input. In the previous two demonstrations, we used a median shift to distort the distributions of the electricity price and the COP. Here, we compare the effect of distorting the distribution of the discount rate using the same approach, with that of applying the Möbius shift approach defined in section 3.2. In the former case, a value of $\delta = 0.05$ is assigned, whilst in the latter, a value of $t = e^{-0.05}$ is assigned with the exponent chosen to coincide with the mean of the baseline distribution. The cdf of the NPV for the median shift case is plotted against that of the Möbius shift case in figure 4.
5 Discussion

Practical tools for expressing probability distortions as a manifestation of cognitive bias have been emphasised. Here, these fall into two classes: where the distortion is modelled as taking place within a particular distributional class via transformations in parameter space, and general purpose distortions. In the latter case, we might also have also looked at distortions of cdfs such as $F(x) \rightarrow F^{\alpha}(x)$ for $\alpha \in (0, \infty)$. Perhaps the most interesting mathematical aspect is the link to stochastic ordering. Our message, here, is that a suitable measure of distortion will be order-preserving with respect to certain stochastic ordering.

In discussions with partners on the ReUseHeat project, for which we are grateful, and within the growing community interested in uncertainty analysis in infrastructure and decision-making more generally, it is clear that the following dichotomy is of great interest. Namely, the distinction between measurable variation and variation arising from expert judgement, whether
accurate or biased. Thus the published efficiency of, say a heat pump, could be inaccurate in being conservative or over optimistic, without any over-subjective, cognitive, influence or “blame”. But, it may still be wrong, because, for example, the measured efficiency in product development may be different from that in actual use. In summary, this paper is a modest, but hopefully useful extension to the distributional tools to capture distortions, empirical and/or subjective.

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References


