Sven Linow

Quantitative Evaluation of Energy Systems

Methods – Solutions – Applications



HANSER

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Preface

Do we want to shape our future within the realm of the possible, or do we simply let it happen to us? Do we want to use the actual state of our living Earth — in which our future will unfold — and the possibilities that our living Earth allows us, as the basis for shaping our future? What spaces of possibility for active shaping do we have today? These questions are at the center of our current societal debates.

The societal discussion on this matter is in a process of finding its way: On one side, voices dominate that are firmly anchored in trust in the magic of technological progress. This progress is supposed to simply solve all problems on its own in due course. This event will occur once progress, entirely without active support, guidance, or direction from the state or society, but perhaps through the action of market forces, produces the solution. On the other side, there are demands for rapid and proactive shaping of the societal framework conditions, in which just solutions for a shared future are actively developed together. Many arguments in this discourse are characterized by a lack of verifiable factual reasoning and quantitative evidence.

The belief in and hope for purely technical solutions addresses today's and future engineers directly. We are the *they* in "they will find a solution." The goal of good engineering education is to enable the consistent use of quantitative methods and factual reasoning. Core competencies of good engineers are the handling of numbers, the quantification of causes and effects, and the ability to make decisions on the basis of factually and quantitatively justifiable arguments. Who among us would want to board a flying taxi whose design was carried out without regard for (technical) rules and is based solely on trust in progress, i.e., on the assumption that a solution would spontaneously emerge from nothing if a problem occurs during the flight.

This is where the present book comes in. It introduces the current state of the spaces of possibility for our future energy supply on our living Earth. For this purpose, it presents quantitative methods that allow us to argue with reliable numbers and verifiable facts. It is understood that the framework within which a future technology is feasible is constrained by the laws of nature, by the earth system and the resources available within it, as well as by the planetary boundaries within which a technically advanced and just human society remains possible. Technical development can only be shaped by society within this framework.

I hope that we begin to address our pressing problems with the necessary seriousness of thought and the appropriateness of action. In this way, we can shape our future within our real possibilities ourselves. The alternative — a solution through disaster, which quickly becomes more probable through simply waiting for ”progress” — seems to me entirely inappropriate. Let us help the new to be born, and let us be willing to let the old go.

Darmstadt, March 2025

Sven Linow

1 Introduction

The sufficient availability of well-usable energy is a fundamental prerequisite for the continued existence of our society. Only through energy do the production, transport, use, and disposal of all our technology become possible. Only through energy available in the future can we manage the accumulating effects of our previous technical actions in the world.

At the same time, the framework conditions for our energy technology are changing. Many other decision-making spaces of our society, and thus those of technology, are also shifting. This is the subject of the present book. The aim of the book is to help you recognize the situation and its requirements, to provide tools and convey skills that enable you, in your role as engineer, to describe your assignments as clearly as possible, to recognize your scope for action and decision-making, and thereby to make the best and most robust decisions possible.

The book is aimed at representatives of all technical disciplines, since every discipline requires not only disciplinary expertise but also fundamental shared competencies: engineers need deep disciplinary knowledge, paired with a broad interdisciplinary foundation on which to work. Therefore, this book provides broad expertise that extends beyond the boundaries of technology, in order to be capable of action and decision-making in the subject areas covered here.

1.1 Core Theses

The pressing questions are: How do we enable ourselves to live a good life and maintain human civilization in the earth system over the long term? How can we respect the natural limits of our living earth and ensure that we live and act within a range of conditions that is good for us?

With regard to our energy system, this can be formulated more concretely:

1. How do we ensure the long-term adequate supply of our society with necessary energy, without excessively adversely affecting the earth system?

2. What resources are available for the future and for the development of our society and our lives over the long term?
3. How do we ensure in the short term that the stable climate regime of the last 10,000 years does not collapse in a way that brings major or existentially threatening disadvantages for us and our society?

These are not purely technical questions. Interwoven with them are ethical questions and questions of equitable distribution that go far beyond technical considerations. We must keep these in mind. The core theses of this book are:

- Time is pressing if we ourselves want to proactively shape a good and just future.
- The pressing problems are poorly defined. They are very wicked problems (see Chapter 2). We must understand this and accept that there are no simple solutions, only alternatives among poor options.
- Solutions to these wicked problems are never purely technical or purely social. They emerge from a combination of both approaches.
- We have long known enough to be able to move immediately to the necessary actions. Many current literature references are intended to provide direct access to this knowledge.
- Waiting now, only to have to chase after the very dynamic developments in the earth system in the near future without being able to shape them ourselves, is an exceptionally unattractive idea.
- Many problems can be described with simple means at sufficient accuracy to arrive at relevant conclusions. Essential for our decisions and actions are human engagement and the assumption of responsibility. This we cannot delegate to our machines.

The focus is on energy literacy, with which we can think, describe, plan, or implement what is relevant. Energy literacy means the competency to grasp energy and energy-related questions in a systemic form, i.e., with their effects and in their orders of magnitude.

1.2 Focus

This textbook focuses on the relationship between the factors considered central to the future of our society, future energy technology itself, the provision of resources for this energy technology, and the ongoing global warming and biodiversity losses. The major changes in these factors will strongly influence the requirements for and the space of possibilities for technology in our future development:

- In the future, regenerative technologies will have to enable the provision of energy for society. This brings major changes for the entire technological base and for the

forms of socially possible use of energy. This has massive implications for industrial uses and the economy. For engineers who design this technology or work with it, it is therefore important to understand the changes and new requirements in order to be able to respond appropriately in their work.

- The effort required for the provision of raw materials is increasing. Many raw materials are not available in the quantities needed for the global technical implementation of all new ideas. Some are seriously scarce. At the same time, modern technology often requires very special materials from partly rare raw materials. Engineers need fundamental ideas about how this may develop in the future in order to be able to respond appropriately.
- The currently rapidly accelerating shift in climate globally and locally is changing the space of possibilities for technical design. Limiting climate warming and necessary climate adaptation require new social and technical approaches. They influence the availability and use of all technically accessible forms of energy globally and locally.
- Our living earth needs space and resources to thrive, and we are completely dependent on it and its flourishing. Here exist limits and requirements for our human appropriation of resources.

These areas are intensively intertwined. The systemic understanding of the dependencies in depth exceeds the possibilities of a classical engineering degree program. At the same time, these framework conditions cannot be ignored. For this reason, key performance indicators are used in the following as a means of reducing complexity. Key performance indicators are today an essential element in many organizations for analysis, planning, and control. They are essential for the execution of projects, for shaping the future of the organization, and for day-to-day and long-term management. Good key performance indicators have high informational value from a technical perspective and enable the structured evaluation and conscious selection of solutions. For this reason, working with key performance indicators occupies an important place — while being fully aware that key performance indicators always represent a simplification.

1.3 Competencies

This book aims to convey the competencies that enable and encourage you to act actively in the world (Biggs/Tang 2011). In order to be able to apply these competencies with confidence, we need a broad base of knowledge. This knowledge can only be accommodated to a limited extent in a book. Therefore, in this book you will find many references from the field of technology into further relevant areas of knowledge. These references are an invitation.

The connectivity to relevant competencies of education for sustainable development has been deliberately incorporated (Brundiers et al. 2021). Systems thinking, strategic thinking, and futures thinking are essential for addressing the questions mentioned above. At the same time, a clear value orientation is taken as a basis here.

All important current social issues are closely intertwined with the secure availability of energy and resources. This is not always directly visible and is often ignored, much to the detriment of the discussion. It is necessary that our ideas and actions for shaping our future are grounded in a fundamental knowledge of energy and resources, energy inputs for actions, and future real availability (energy literacy). Many meaningful technical or scientific statements on resource use, the provision of energy, and system effects are only possible on the basis of a fundamental understanding of energy. The application of fundamental knowledge and methods of thermodynamics in the discussion of energy-related topics is a sign of seriousness of thought and effort.

Evidence-based decision-making processes — i.e., decisions in which substantive arguments count — require robust technical facts and methods. As engineers, we take on the role of bringing discussions of technical problems back to what is actually technically feasible. For this we need a robust framework of skills and knowledge. For the methods and examples presented here, a small part of the concepts, definitions, and formulas from an introductory thermodynamics lecture is required as a toolkit.

The goal of good teaching/learning situations is to convey to students genuinely applicable competencies, whereby these competencies can only be applied if, alongside them, a base of usable knowledge about interrelationships is available. We learners must acquire these competencies ourselves in our very individual learning process. The hope associated with this book is that real, current examples of high technical and social relevance for one's own further life provide additional motivation that carries you through the not always easy material.

Specifically, the following competencies are to be conveyed:

1. The fundamental methods from an introductory thermodynamics lecture are applied. This is intended to encourage you to apply the systemic perspective, which is so central to the thermodynamic method, to a wide variety of problems.
2. The ability to gain orientation in poorly defined problems or unclear situations is very helpful in professional life. In addition, it is necessary to first roughly estimate numbers in order to better understand and narrow down the problem and the task. This situation differs greatly from studying, in which usually only clearly and completely specified tasks need to be solved. The approaches used here are suitable for initial estimates. They are ideal for narrowing down a problem, comparing solution variants, and thus laying the foundation for good communication.
3. Many of the methods and approaches presented are based on key performance indicators. The construction of the key performance indicator is often the focus. The competency conveyed here is the construction of good and informative key

performance indicators as well as the assessment of whether a key performance indicator carries a relevant statement. In the best case, you yourself take influence on the design of key performance indicators and can raise inappropriate, imprecise, or poorly defined key performance indicators to a level appropriate for the problem.

4. The scientific method is briefly introduced and pitfalls in one's own research are discussed. The literature references in this book are kept (as far as possible) up to date and make use of specialized scientific literature from various disciplines. This is intended to encourage you to include all forms of literature while at the same time evaluating sources with the appropriate critical distance.
5. The examples and the numbers calculated therein are deliberately chosen to be large. In this way we practice dealing with initially unimaginably large numbers. It represents its own challenge to repeatedly bring these large numbers back to a tangible basis.
6. Many of the results and values determined here are not very precise, but always sufficiently robust to proceed to further evaluations and conclusions. The ability to work and argue with values that are not absolutely correct but sufficiently accurate represents one of the fundamental competencies for engineers.
7. Dealing with deliberately global problems is intended to help overcome a common obstacle in the discussion of solutions to large problems: in public discussion, the smallest solutions are often celebrated in detail, which upon systemic examination make no contribution due to their changes being minuscule compared to the global problem. Recognizing this is a competency in itself.
8. The problems discussed are at least of regional and often of global relevance. Many of the problems addressed are not small independent tasks, but global problem structures in which there are feedbacks and interactions that make everything confusing and complicated. Recognizing problems as global and interconnected is an essential competency when it comes to shaping the future.
9. At many points, relevant cross-references to other topics and aspects are inserted. This is intended to show the nonlinear feedbacks through which many global problems are so difficult to grasp and address.
10. The connection between technical and social aspects is of fundamental importance for engineering education. Good engineers possess a clear attitude and ethics. Developing and enabling this gift can only succeed if the connection between the technical and the social sphere is regularly and vividly presented.
11. The image of the living world or the earth system is developed from a natural science perspective. This illustrates the applicability of thermodynamics to natural and living systems. A fundamental understanding of the essential processes and sequences in the earth system is the basis for the further analysis of the effects

of human action. Only from an understanding of the earth system is it possible to grasp many particular aspects of the problems addressed here.

12. Real and large problems are never simple tasks. They are wicked problems that resist simple approaches. It is an essential step in understanding to recognize a wicked problem as such, rather than believing in simple solutions.
13. Many problems can be approached with relatively simple tools. Often rough calculations and simple models in combination with thorough reflection and acceptance of uncomfortable possibilities are sufficient to obtain the important insights.

1.4 Structure

Part I: Fundamentals, Methods, Key Figures, and Framework Conditions

Part I provides many fundamentals that together create a basis with which technical and societal questions of the transformation of our energy system can be addressed.

Chapter 2 is not technical. It conveys essential concepts for understanding large problems such as the transformation of our energy system. For this purpose, an established classification of problems is introduced. This makes clear that this book focuses on wicked problems that resist simple, purely technical solutions. To this end, it contains essential foundations for the constructive, evidence-based, and solution-oriented handling of problems and the procurement of reliable facts. We want to approach our problem in an evidence-based and scientific manner. This requires a critical approach to sources and information.

In Chapter 3, the essential contents of thermodynamics necessary for understanding the subsequent chapters are summarized in brief form. The chapter cannot replace a thermodynamics course. All contents are presented in a didactically more accessible and technically more in-depth form in my textbook *Angewandte technische Thermodynamik* (Linow 2022). There, a large number of examples with a direct reference to the transformation of our energy system can be found.

Chapter 4 offers an introduction to the life cycle of products. Further central concepts are the availability of resources and the technology readiness level of solution ideas.

In Chapter 5, central energetic key performance indicators are introduced. Key performance indicators allow a first good comparison when they have been determined cleanly and reliably.

Chapter 6 summarizes descriptions with which a growing or shrinking quantity and its behavior over time can be described. For this purpose, aspects of growth for a number of required resources are examined. The understanding gained here is intended to help describe and evaluate the speed and limits of transformation processes.

In Chapter 7, energetically fundamental relationships of our earth system are introduced. We want to live and operate economically in this system in the long term. Therefore, the focus is on relevant subsystems and their limits.

Part II: Shaping the Transformation

With wicked problems, the problem description is part of the solution attempt. Therefore, the problem description cannot take place at the beginning, but waits until here.

Chapter 8 introduces hard framework conditions within which future civilizations and their energy systems will operate. To this end, it discusses important concepts and classifies their possible contributions to a transformation.

Against this framework of possibilities and requirements, the relevant technical concepts for the energy infrastructure are then introduced:

In Chapter 9, the focus is on the provision of heat from fossil fuels, biomass, and other sources.

The potential of regeneratively produced hydrogen and synthetic fuels produced from it is the subject of Chapter 10. Hydrogen and its derivatives have a special role and are therefore deliberately presented separately from fossil fuels.

Chapter 11 focuses on hydropower and wind as direct conversion of mechanical power into electricity, as well as their potential and requirements.

In Chapter 12, the main focus is photovoltaics. For this purpose, further fundamentals on solar irradiance are first introduced.

Every energy system contains storage. In Chapter 13, storage options for electricity are the focus. Synthetic fuels as storage are the subject of Chapter 10.

Chapter 14 addresses the topic of reducing harmful effects on the earth system and the associated energetic costs. First, it deals with flue gas treatment as it is common today. The second focus is then on dealing with carbon dioxide and other greenhouse gases.

Chapter 15: Outlook and Spaces of Possibility

Chapter 15 deals with the question of how quickly we can shape the transformation of our energy system and what we need for it. Chapter 2, Chapter 7, and Chapter 8 deliberately go beyond the engineering framework and introduce societal aspects that are essential to the problem. In Chapter 15, we pick up some of these threads and also some technical threads and bring them together.

Chapter 16 (List of Symbols) and Chapter 17 (Appendix)

Chapter 16 contains a list of the constants, symbols, and SI prefixes used in the book. Chapter 17 (Appendix) contains many useful data – useful for the worked examples, but also for one's own work and analyses.

Examples

The examples illustrate the application of many introduced concepts. At the same time, they serve to present concrete environmental impacts. No technology works without problems. Concrete examples are chosen as a place to illustrate this. The numerical values used in the examples have been determined to the best of knowledge; nevertheless, they are sometimes imprecise, outdated, or there are differing values from

other sources. Often they are average values that must be verified upon closer examination or during analysis. The results of the examples are therefore also estimates; however, they are sufficiently robust to allow conclusions to be drawn.

1.5 Acknowledgments

Even the first edition of this book was the result of a long personal process. Since then, much has happened in our world, so that a new edition with a thorough revision of all contents became worthwhile. I am very grateful that Hanser Verlag opened this path and I am delighted by the outstanding support, in particular from Julia Stepp and Tim Borck.

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Special thanks go to all my students, who have learned the subject of this book with me and whose many questions made this project possible in the first place. Their questions, their sometimes unexpected approaches, their discussions and learning processes can be found in very many places. In addition, there are a large number of student theses that I was able to supervise. The discussions associated with them have provided me with new insights and ideas, some of which can be found in the book.

My brave family has once again endured a father and husband who was at times absent for months. They put up with an enormous drifting dune of literature in their

living room and a completely covered dining table. Yet they always encouraged me to tackle and complete this project – awesome!

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Part I – Fundamentals

How do we as a society want to address the pressing social and technical problems associated with the transformation of our energy systems? Part I provides you with the foundational knowledge needed to think more deeply about this system. The complexity of our historically grown energy system permeates large parts of our society and our planet. In Part I, we approach the description of the system, with each chapter opening its own perspective. The energy system is subject to constant change, but in order to make it fit for the future, we will need to strongly accelerate this change and adapt to the possibilities of life on this planet. This is the subject of Part II.

The aim of this book is to present important tools for evaluating energy technology and to illustrate their application. In particular, methods are to be provided that estimate, from a thermodynamic perspective, the extent to which an energy technology achieves important goals and what environmental impacts it generates in the process. A systemic perspective is consistently required for this purpose. This systemic perspective is established through clearly chosen system boundaries and methods that describe the life cycle of a product as completely as possible. In this context, the goal definition from Chapter 8 already has a retroactive effect, meaning that the focus here is primarily on those fundamentals that will later help us on the path toward the goals yet to be developed.

Chapter 2 examines what exactly characterizes these relevant, very difficult problems. It offers guidance on the question of how we can succeed in establishing reliable facts, and it addresses the question of how we can generate good solutions. This also gives us a way to scrutinize existing solution approaches and find out how good they are.

Chapter 3 provides a brief introduction to thermodynamics. Here, important terms used in the following chapters are defined and fundamental relationships are introduced. The chapter cannot replace a genuine introduction to thermodynamics. It is rather to be understood as a refresher or an invitation to engage more intensively with this method and description.

Chapter 4 delves deeper into the systemic perspective. The focus is on the life cycle of energy and of components of the energy system. The foundation of technology is the availability of resources. The concept is therefore introduced in a very general way and then explored in more depth specifically with regard to metals and their future supply. With a view to technological developments and the question of when new technologies can solve today's problems, the technology readiness level is introduced as a perspective.

In Chapter 5, the fundamentals of energy and life cycle are brought together to introduce important key figures for energy systems. These key figures are extremely helpful for describing and comparing different technical options.

Transformation and change always involve growth and contraction. Chapter 6 provides tools with which we can describe this. In doing so, we cannot avoid the question of whether long-term economic growth is planetarily possible.

Chapter 7 offers an introduction to the description and magnitude of energy flows in the earth system and to the relevant human influence on these. Our aim is to understand processes and to be able to estimate orders of magnitude. This too is an invitation to engage more deeply with these topics.

The goal is to make sound, robust decisions that are positive for as many people as possible, in order to address the major future challenges and manage them as effectively as possible. To do this, we must not only generate possible solutions, but also analyze them with regard to the problem itself, i.e., with regard to the possible outcomes, results, and consequences. We do this generally on the basis of facts, taking into account applicable regulations, laws, standards, and rules, and using the scientific method. In doing so, we also orient ourselves toward engineering ethics as most recently formulated by the VDI in 2021. We begin with this aspect.

2
Problems and Solutions

The subject of this book is major challenges that at first appear to be technical in nature. They are major challenges because, on closer inspection, their solution becomes very difficult, because technology alone is not sufficient for a solution, because technology may be part of the problem, because there is often no good solution at all. Such challenges are difficult to grasp and even more difficult to solve.

Problems can be divided into tame problems and into wicked problems. In English, *tame problem* and *wicked problem* are used as established terms (Rittel/Webber 1973). They have been translated here.

- *tame*: The term *tame* is deliberately intended to evoke associations such as friendly, obvious, cuddly or nice, and to suggest that this type of problem has completely submitted to human design.
- *wicked*: On the other hand, *wicked* illustrates the character of those problems that elude all human control in a devious, unpleasant and unpredictable manner, and unfold their effects unexpectedly, differently than planned and with force, regardless of whether we ignore or deny them.

In VDI 2221-1, the terms ”task” and ”problem” are used: tame problems or tasks in the sense of VDI 2221-1 are fully described by the problem statement, a solution exists, and there are unambiguous criteria for whether a proposed solution is right or wrong. This is the type of assignment we are primarily confronted with during our studies, but which engineers encounter rather rarely in their professional daily lives. VDI 2221-1 understands as a problem those technical challenges or specific design tasks for which there is no simple solution. Even these problems require their own systematic approach, but they are often not wicked problems in the sense of the definition used here.

Wicked Problems

The problem areas focused on here — energy supply, climate, biodiversity and resources — give rise to wicked problems, as they as challenges mostly go well beyond the problem definition of VDI 2221-1. One of the goals of this book is to illustrate this.

Wicked problems are characterized by the following ten criteria (Rittel/Webber 1973, slightly revised, see also Table 2.1):

1. There is no complete or correct description of the problem. The description is itself part of the solution, since the solution inherently contains a specific definition of the framework for action, the actors, the causes, etc.
2. There is no unambiguous criterion for when the solution has been reached. The solution is frequently the state that is arrived at after a certain amount of effort and that is now implemented after the resources provided for finding the solution have been exhausted.
3. Solutions are neither right nor wrong — they are good or bad. Most often they are better or worse. Criteria for good and bad frequently arise from a normative or ethical framework.
4. There is no unambiguous evaluation of how good a solution is. With tame problems, deviations from the ideal solution can be determined and individual proposed solutions can thus be classified. With wicked problems, the consequences of the solution can only be recognized in hindsight, since the effects propagate in complex ways throughout the entire affected system. Frequently, the implemented solution cannot be compared with other proposed solutions.
5. Every implementation counts in full. There is no possibility of approaching the solution through trial and error. Every implemented solution or measure leaves traces in the world that cannot be undone and that influence and distort every subsequent attempt.
6. There is no countable or fully describable set of potential solutions. There is no well-describable set of operations by which a solution is reached.
7. Every wicked problem is unique. There are no classes of similar or similarly solvable wicked problems.
8. Every wicked problem can be regarded as the symptom of another wicked problem. It follows that improving one problem creates difficulties in addressing the next.
9. If we describe a wicked problem as a deviation from a desired different state, we thereby already determine solution paths or exclude possible solution paths. This happens solely through the framing of the problem.
10. Errors in the solution often cannot be tolerated, as they have direct effects on the circumstances and lives of people. Those seeking solutions bear a high responsibility that their solution works.

Thus the definition of the wicked problem goes significantly beyond the problem definition of VDI 2221-1. In particular, wicked problems always contain social effects or repercussions that cannot simply be resolved. The central thesis of this book is that all relevant technical and social problems are wicked, at least with regard to a trans-

formation of our energy supply. Constraining boundary conditions arise, among other things,

- From the second law of thermodynamics, which sets natural limits on many possibilities (see Chapter 3),
- From the limited availability of resources (see Chapter 4, Chapter 5 and Chapter 6),
- The necessity of remaining within planetary boundaries (see Chapter 8), as well as
- From social and ethical limits.

The magnitude of the pending required changes and the complexity of the links between social and technical aspects means that all problems of the Great Transformation of our energy system are wicked (this sounds almost like a version of the second law of thermodynamics, and perhaps it also follows from it in some convoluted way).

Table 2.1 Classification of Problems

Aspect	Tame problems (*tame*), tasks	Wicked problems (*wicked*)
Problem description	unambiguous closed complete	An unambiguous or complete description is impossible. The description depends on the perspective, the attitude, and the chosen approach to a solution. The problem can only be fully described as part of a solution.
Solution	unambiguous closed	Often there is no solution, only better or worse ways of dealing with the problem. There are any number of possible solutions.
Deviation from the solution	Clearly determined The error can be calculated immediately.	It is unclear when a different solution begins. It is unclear from what degree of deviation the proposal is no longer a possible solution.
(Numerical) simulation	Well suited	A simulation is never complete and the model is inadequate: missing aspects, consciously or unconsciously chosen assumptions, and simplifications used distort the simulation. The result may be irrelevant.
Example	Number, mass, volume	What is the right way to raise my child? What education should I choose?

Capturing Wicked Problems

In many political or technical discussions, complex wicked problems are presented as simple tame tasks for which there is a correspondingly simple solution or product.

The aim of this book is to convey a fundamental, careful, and ethically appropriate approach to wicked problems and to examine proposed solutions with the necessary attention. For this purpose, we can ask ourselves these questions:

- Is the problem meaningfully and completely described? Is the cause clearly identified? Is the symptom a cause or a consequence of the problem?
- Is the proposed solution appropriate to the problem? What purpose does this proposed solution serve? For whom is this proposed solution useful?
- Is the problem really a simple tame problem for which there is only this one solution, or is it in reality a wicked problem?

AI So-called artificial intelligence (AI) cannot help us here: AI has no complete description of the problem. AI has no model that maps all interrelationships and feedback effects. AI has no *skin in the game*. AI inevitably produces bullshit. AI has no consciousness and therefore cannot deliver decisions on ethical issues (VDI, 2021; Bridle 2019; Townsen et al. 2024; Zhou et al. 2024). More on digital technology can be found in Chapter 8.

2.1 The Scientific Method

In order not to be confused or overwhelmed by wicked problems, it is necessary to approach them in a structured manner and in this way to accumulate the necessary knowledge about the problem, the entanglements of the problem with other areas of the world, and about possible solutions. The scientific method is particularly well suited for this, since unlike other approaches it is fundamentally systematic and error-oriented, and since in the scientific approach the result is not predetermined. The goal of every university education is to be able to think and work scientifically (even if this sometimes feels more like vocational training at the bachelor's level).

Essential in this regard, alongside solid professional competencies, are the critical handling of sources (Section 2.2) and the capacity for personal reflection. We need critical distance from our own emotions and needs in order to prevent them from unconsciously influencing our thinking and anticipating results. At the same time, we need our emotions as an ethical compass.

In science, a fundamental assumption is that the physical world exists and has a very concrete, unambiguous form and shape, entirely independent of how we ourselves wish to see or are able to see it. To recognize this real world ever more clearly — that is something we can and should attempt.

If we want to solve the wicked problems ahead of us, then we must understand the world as it is, with all its challenges and inconveniences, as well as possible. The only reasonably reliable path to this that we know of so far is the scientific method. The direct application and consequence of this thesis is that one's own opinion cannot be

the starting point or the center of one's own theory of the world. The world does not orient itself according to my own opinion; rather, I must grasp the world as it is in order to develop a current theory of the world based on a sound scientific analysis of reliable findings. My individual theory is thus dependent on my current understanding of the world, and I must change my theory of the world whenever I receive new reliable findings. Always.



Scientific method

The scientific method is clearly defined by a fundamental attitude and general approach:

- It seeks answers to questions from nature and technology, always looking to nature or technology itself for those answers.
- It presents preliminary answers to its questions — so-called hypotheses — and tests, through careful observation or through repeatable experiments, whether and to what extent these hypotheses are reliable answers. Only this form of confirmation of hypotheses is recognized.
- All results that build up into a theory as a structure of verified hypotheses are always regarded as provisional.

Every theory is valid only until it is refuted by new observations or experiments. As long as it is valid, we should use it — even at the risk of contradictions arising. From these contradictions we can then further improve our scientific description of the world by first understanding where the contradictions come from. Afterwards we can adjust our theory so that these contradictions diminish or disappear.

The aim of this book is to approach questions always from a scientific perspective. This often already requires courage. In many discussions, fundamental assumptions are taken as given: there is often a felt consensus about what may still be discussed and what is already settled. Questioning this consensus can already provoke massive rejection within a social group or organization. Many social groups and organizations have belief systems that predetermine decision-making processes. Particularly within groups, acceptance of the fundamental belief systems is often a prerequisite for participation. A scientific approach, however, requires that we ensure all our assumptions are correct. We must verify and question. This is sometimes uncomfortable or difficult.

Any theory that cannot be confirmed or refuted by experiments or observations in the real world is not scientific. In the subject area of this book, we can confirm or refute everything through experiments or observations.

Any theory that is also based on supernatural forces or magic is not scientific. Magic keeps creeping into our world and into our thinking. It is a laborious process to keep reassuring oneself that one's own thinking is not guided by ultimately magical expectations or hopes. In social discourse, magical hopes and expectations are always present. Identifying these elements is already a major and strenuous step.

2.2 Recognizing Reliable Sources

It can be difficult, especially at the outset, to obtain reliable information on a topic. Scientific specialist literature would first have to be found, and it can quickly become too complicated as an entry point. This section therefore describes further possible sources and is intended to help you strengthen your judgment.

Many communication channels follow the rule: *"Whoever shouts loudest is right."* This is consistently applied particularly in the realm of the attention economy of digital platforms, in social networks, in politics, and in forms of popular reporting: texts often also target emotions such as anger and outrage directly, which are intended to prevent any critical distance from the text (Törnberg/Chueri 2025). In most cases, simple solutions are simultaneously presented with which the problem addressed would be directly solved. The solution (or the truth), this form of reporting implies, is being prevented by evil, stupid other groups or media. In the process, the information about the actual occasion is already heavily filtered. Particularly within opinion bubbles and echo chambers in social media, these emotions then quickly amplify — and every network in social media has the tendency to be such an echo chamber of like-minded people, since any form of deviation from the general outrage is immediately and emphatically punished there with social ostracism (Bridle 2019). That is not scientific.

Social media Common social media are provided by commercially oriented actors with a strong political agenda of their own. Here the primary goal is to bind users as intensively as possible to the medium in order to show them as much lucrative advertising as possible. To achieve this, the hidden algorithms that suggest content to us are designed to deliver content that matches the interests and emotional needs of the individual as closely as possible. Very often these are contents with a high sensational or arousal component. In particular, the algorithms are indifferent to the truth content of individual pieces of content — there is deliberately no distinction between bullshit and facts (on bullshit see Frankfurt 2020). What is essential is to clearly identify users and to know them as precisely as possible. Through selection and use, a user profile is thus created. This user profile then shapes what users are able to see of the world at all. As users, we thereby shape ourselves and our world, and live in an information bubble without any contact with the real physical world (Bridle 2019).

Original source or hearsay The scientific method demands an approach that runs diametrically counter to this description of the world and this form of information gathering. In particular, a scientific approach requires first of all knowing and evaluating the original sources. Before I as a reader allow myself to be overwhelmed by the expected outrage over a terrible new piece of draft legislation, I first read the original draft and begin to analyze it using my own criteria. If I lack information to understand the text, I research it, where possible using additional scientific sources. I maintain a critical distance toward every source. This critical distance is reflected in the fact that

I do not blindly believe what is stated in the source, but wish to be convinced by arguments.



Critically examining sources

When critically examining sources, we should ask ourselves the following questions:

- Is the source internally consistent?
- Does it accurately and sufficiently completely reproduce other sources, contributions, or opinions?
- Does it place other contributions sufficiently clearly and correctly in the necessary context?
- Are the methods used here appropriate for addressing the topic?
- Can the results be correct?
- Are the conclusions logically derived from the results?
- Are the motivations of the authors comprehensible and sufficiently clearly disclosed?
- Are analysis and opinion distinguishable from each other?

Studies Good studies are reliable scientific representations. This applies when they are conducted by an independent research institute and when the client has not predetermined the result. Good studies follow the logic of scientific texts and disclose all framework conditions. Good studies are complete, i.e., they also contain information about deviating results and interpretations, failed experiments, and difficulties in implementation.

Journalistic Texts

These texts follow a different logic and are therefore not always suitable as reliable sources: Authors often attempt to document their ”objectivity” by presenting the subject they are reporting on as a dispute between two poles (Dean 2012). This is a form of representation that originates from political reporting and is already unsuitable there for describing problems or developments (as false balance). This perspective must be evaluated very critically with regard to the topics of this book: If the position that is actually supposed to be reported on is a scientific consensus, then the authors, if they want a contrast, have no choice but to find a second position that lies far outside the scientific consensus. Such positions lying far outside the scientific consensus can easily be found today via the internet: self-promoters, quacks, magicians, merchants of doubt (Conway/Oreskes 2012), or cast pseudo-scientists offer themselves there. While scientists must speak of *probability* (see box), the opposing side is allowed to be *absolutely convinced*. Unlike scientists, they also do not have to report on their conflicts of interest, or even obvious self-interests are simply ignored. What aspires to be objective reporting quickly becomes a vehicle for untruth or creates the space for spreading actually nonsensical positions. In addition, journalists are sometimes forced to report on topics to which they have no specialist access of their own. They are therefore some-

times unable to recognize obvious falsehoods, untruths, bullshit, or nonsense. This applies all the more when it comes to rapid reporting.

Good journalistic texts draw a sharp distinction between reporting and opinion. The previous paragraph highlights the danger of an apparently ”objective” presentation that reduces topics to opposing poles. This can also appear in an otherwise clean and fact-based text that clearly contains no opinion of its own. The opinion might then be found in a text marked as a commentary elsewhere. However, this clean approach is no longer always maintained even in quality media, and opinion and reporting then merge into one another. Many media outlets already abandon minimum standards out of consideration for revenue or the political agenda of their owners and begin with emotion (Törnberg/Chueri 2025).



Describing probability and certainty

Scientific texts have an established form for expressing how certain a statement is or how significant a result is. The formulation ”very likely” may colloquially be rated at a 20% probability of occurrence on a good day, but in a scientific text it means a value well above 90%.

The fact that scientific texts couch their statements in probabilities is not an indication that the situation might be entirely different, but follows from the inherent logic of science, which always represents an approximation to the world and accepts that things may be otherwise. This makes statements from scientific articles considerably more reliable, truer, and more useful than so-called ultimate truths from other sources.

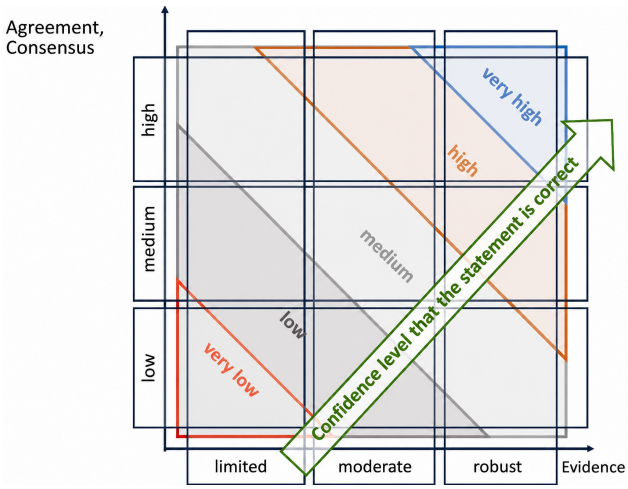


Figure 2.1 The confidence level for a statement depends on the aspects of agreement (within the panel) and evidence (which, how good, how reliable, how consistent) (based on Mastrandrea et al. 2010).

In scientific publications, the probability and the certainty of statements are often expressed verbally. The reports of the Intergovernmental Panel on Climate Change (IPCC) are a good example here. Table 2.2 lists the terms used there and their definition for probability along with a translation. Based on two independent parameters — the existing evidence for a statement on the one hand and the degree of consensus among the experts involved on the other (Figure 2.1) — the confidence or certainty with which a statement is made in the IPCC reports is additionally defined. This clarity and traceability is what distinguishes good scientific sources.

Table 2.2 Standardized Terms of the IPCC to Express the (Likelihood of the Outcome) (Source: Mastrandrea et al. 2010)

Term (EN)	Probability of occurrence
Virtually certain	> 99 %
Extremely likely	> 95 %
Very likely	> 90 %
Likely	> 66 %
More likely than not	> 50 %
About as likely as not	33 % to 66 %
Unlikely	< 33 %
Very unlikely	< 10 %
Extremely unlikely	< 5 %
Exceptionally unlikely	< 1 %

Science and technology journalism A particular difficulty arises in reports on new technical developments: in order for scientists to gain attention, they must present their results as directly relevant. Journalists, in turn, find it extremely difficult to report on a development that is not directly and concretely applicable. This creates the risk that the potential of an invention or discovery is significantly exaggerated in their report. This effect explains the frequent appearance of ultimate solutions and silver bullets in the press. This need is additionally exploited by start-ups to push themselves forward and raise capital: unfounded promises are gratefully received (and the massive limitations in the fine print are simply overlooked).

If we read uncritically through the technology section, we will all soon be traveling to the moon in autonomous taxis and sourcing our raw materials from Neptune. The impression is created that there are technical solutions to all problems, which could practically be rolled out tomorrow morning. Some readers feel confirmed in their optimistic view of the future, while others become cynical, as these wonders soon dissolve into thin air. Such reports always have a kernel of truth (a study or a planned experiment in a first demonstrator), but everything has simply been presented more

optimistically and much more simply than it actually is. The only remedy here is to seek out the original source and evaluate it yourself (Dean 2012).

Value of journalistic contributions Criteria for good journalistic work are presented, for example, in the press code of the German Press Council. These requirements can be used directly as a benchmark to assess whether we can use a journalistic article, a blog entry, or a video as a source. Good journalistic sources have very high value for tracking current developments, such as the political implementation of measures. However, day-to-day reporting is at the same time hardly able to identify long-term trends or causes, so that both perspectives become important here: it is only scientific texts or long-term journalistic contributions that provide important perspectives.

Journalistic contributions offer, at best, the significant opportunity to get to know personal perspectives and experiences. Scientific literature must, for methodological reasons, largely forgo this. Only through the personal experience and perspective of key actors and those affected can a complete picture emerge. We need these perspectives in particular to prevent a lack of imagination, which characterizes many contributions to the topics of this book.



You can find the German press code in its current form here: *https://www.presserat.de/pressekodex.html*

The core is respect for truth and human dignity: *"Respect for truth, preservation of human dignity, and truthful information for the public are the supreme commandments of the press. Every person working in the press upholds on this basis the reputation and credibility of the media."*

Other important aspects of the code are thoroughness of research, separation of activities, and the separation of advertising and editorial content. Not all media succeed in this and in other requirements set out therein. Some media deliberately position themselves clearly outside of it.

Politics

In politics, a worldview is widespread that assumes all facts are negotiable. Negotiable means that facts are the result of a negotiation in which the more powerful determine the "facts" for everyone through money, influence, power, threats, or coercion.

Accordingly, in politics opinions are often fixed, or opinions are not oriented toward facts in the sense of scientific findings. Potential facts are then adapted to the respective prevailing opinion. Autocratic regimes display this behavior particularly clearly and distinctly. A hallmark of autocratic regimes is the weakening or destruction of scientific institutions. At the same time, we find opinionated politicians with little respect for scientific knowledge and little capacity to question their own position everywhere. This opinionatedness and the associated mercilessly self-centered determination to prevail are often regarded as strength of character, although they would be better de-

scribed as ignorance, stupidity, or in terms of psychiatric diagnoses. This is not a helpful position or preferred method for addressing the challenges of future sustainable development, but rather endangers our future (DeLay 2024).



Structure of scientific journal articles

Scientific articles follow an established structure and argue with logic. For this purpose, they use a specific language. Both clearly distinguish them from other forms of written communication. The structure of a scientific article is clearly defined so that readers can understand the argumentation as precisely as possible and follow the arguments in detail (if they wish to do so). At the core, it is about being able to understand how the authors arrived at their conclusions:

1. The research question and the motivation for the investigation are clearly presented at the beginning: what is being analyzed and for what purpose?
2. An overview of the relevant literature and the state of research is provided. The focus is on fundamentals that are considered common consensus, as well as on important recent contributions. With regard to the problem being analyzed, gaps in knowledge, open questions, and also points of contention are indicated where relevant.
3. The methods used are presented (often with reference to other literature) in such a way that readers can apply these methods themselves – so that they can ultimately repeat the investigation independently.
4. The results of the analysis are presented clearly. This is a purely factual presentation of data, figures, calculations, and simulations.
5. In the evaluation, the results are analyzed with regard to the research question. Only here is an attempt made to provide an answer to the scientific question. Here, recommendations for action can be developed from the hypotheses thus generated. The investigations of others are incorporated here, confirmed, extended, or rejected.
6. At the end of the article are the conclusions, which should develop logically from what has preceded them.

Enforcing this logical structure and ensuring that the chain of argumentation is coherent and comprehensible is the task of the peer review process, to which the vast majority of scientific articles are subjected. Peer review means that specialist colleagues critically read the article before its publication and assess whether it is suitable for publication based on the criteria mentioned, or how it would need to be revised in order to be published.

The language of scientific literature is very objective and restrained. The goal of the presentation should be to avoid confusing critical readers with emotions, but rather to make the technical content as accessible as possible. Respect for readers is expressed in the fact that they are encouraged to draw their own conclusions.

2.3 Social Aspects of Technical Change

Wicked problems and their solution variants have the property of creating affected people and violating interests. This makes early communication of this aspect important. Not In My Backyard (NIMBY) and also Build Absolutely Nothing Anywhere Near Anything (BANANA) describe current social trends. There is always a group that argues why something may actually be good in principle, just not here or not now. These groups usually find a receptive audience; they perform well in media systems or serve the expectations and interests of others. Sometimes they raise aspects that are worth considering but have either been overlooked or not communicated so far. Sometimes they are instrumentalized by other interests. Sometimes they retreat into their own social echo chamber and are no longer receptive to arguments from outside. Sometimes something is simply instrumentalized.

Due to the low power density of natural energy flows, it is not possible to make infrastructure for the provision of energy and for the generation of electricity from sustainable sources small. Due to the power losses when transporting electricity over longer distances, it is appropriate to spatially couple generation and demand. This represents a fundamental conflict that in most cases cannot be resolved purely technically but must be negotiated socially.

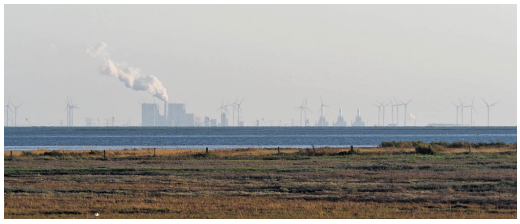


Figure 2.2 Energy landscape Eemshaven, Netherlands

Figure 2.2 shows Eemshaven in the Netherlands from a distance of 30 km. Eemshaven is located far from all population centers in the Netherlands. There is a coal-fired power plant (rated capacity 1560 MW, allegedly CCS-ready, see Chapter 14), a total of eight combined cycle gas turbine power plants (CCGT), three of which with a combined rated capacity of 1311 MW are visible in Figure 2.2 (the five additional CCGT power plants have a further combined rated capacity of 1750 MW), and approximately 50 wind turbines (combined rated capacity 156 MW). Figure 2.2 illustrates the size ratios and the space requirements of the individual technologies well. It also illustrates how a society pushes its energy generation to the sparsely populated periphery and out of the population's sight. There in the periphery, sacrifice landscapes then emerge that we would not want close to us in the center (Brandt/Wissem 2017).

In our society there is a lack of understanding of the magnitude of energy quantities or energy demand. (Populist) politics shamelessly exploits this. Many of the proposals being discussed show that the magnitude of one's own demand, the demand of one's own city or one's own country is not understood. The only way forward here is to calculate these numbers, state them, and illustrate them well. The following is intended to provide you with helpful data and methods for this task.



Energy demand

A person requires approximately 100 W or 10 MJ per day for their supply of energy through food in order to stay alive and healthy. This corresponds roughly to one kilogram of bread (Figure 2.3). The annual per capita primary energy consumption in Germany is 45,000 kWh. This corresponds to the energy content of 45 such loaves of bread for each of us per day. Our technology requires 45 times as much as we do. For the annual per capita final energy consumption of 31,000 kWh, we would need approximately 30 energy slaves for each of us to do this work for us.



Figure 2.3 Daily energy demand of a person

2.4 What Do We Know?

In a simple representation, four categories of knowledge can be identified (Figure 2.4). Here it is two axes that determine what we know:

1. The simple axis of what is actually known: What knowledge and insight is really available and usable?
2. The difficult axis of what we know and want to know about our state of knowledge

From this, the four categories develop in Figure 2.4:

- **Known knowns:** The first category is established, secure knowledge, whereby this knowledge is continuously changed, expanded and adapted, at least from a curious or scientific basic attitude. New findings must be integrated, old certainties dissolve and some competencies are lost over time.

- **Known unknowns:** The second category consists of known knowledge gaps. In the best case, we make an effort to fill these, or we turn to people who can take on this task for us. Of course, every gap we fill will cause our established knowledge to change. Therefore, the first defensive battles are already fought here, intended to prevent learning.
- **Unknown unknowns:** The third category consists of all those things that we objectively cannot know that we do not know. This source of genuine surprises may currently be estimated as rather small.
- **The repressed:** The fourth category is the knowledge that we have, indeed must have, but which we consciously or unconsciously and always at our own risk ignore. Shifting as much of our more difficult or critical knowledge here as possible is the result of our own inertia and the goal of trolls, populists and merchants of doubt.

In Chapter 8 we look at what possibilities we have to shape a good future. It will be essential that we cannot afford ignorance if we want to shape a humane and good future. Keeping one's own repressed knowledge to a minimum requires reflective capacity, humility and a very low bullshit tolerance in all of us.

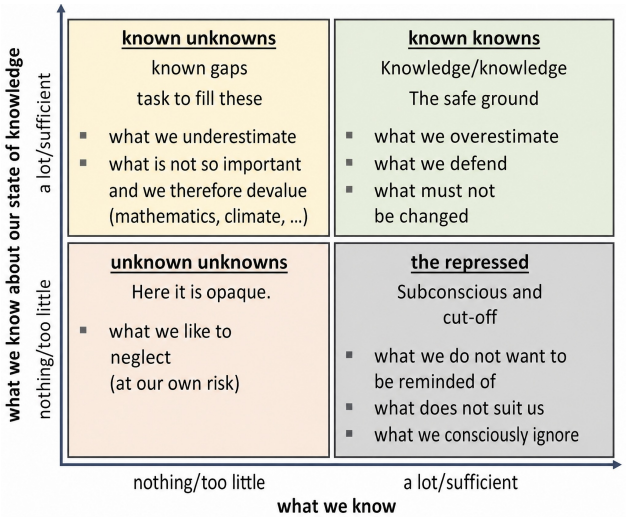


Figure 2.4 A portfolio of our knowledge

2.5 Environment and Technology

We humans, our environment and our technology – these are not separate spheres, but all three exist only together in the earth system and interact closely. Therefore, the scientific method uses the same theories for their description and analysis. The same laws of nature apply to all three.

Long since dismissed as false, but still powerful systems of thought in the Western world separate between humans and their technology, between body and mind, and between humans and nature as their environment. If we view the world from a thermodynamic perspective, it is possible to describe humans or humans together with their technology as a system. However, these are open systems that are in direct and very close exchange with their (living) environment:

- The three systems are in constant and very close exchange of substances. Nothing remains confined to one area.
- Energy permeates all three domains and flows across all their system boundaries.
- Through the exchange of energy and entropy, the exchange of effects takes place within the common earth system. At the same time, the exchange of entropy can be used to describe the impact of one's own actions in the world.

The common system is the critical zone of our earth (the area of the earth full of life) and we are absolutely dependent on the state of this critical zone. A meaningful hierarchy of the systems cannot be achieved; however, we humans with our technology and our economy are by now a very large and powerful part of the earth system.

Anthropocene Environment and technology interact with each other at all their interfaces and in an unmanageable diversity of processes. Due to the mass, size, and extent of energetic flows of the earth that pass through technology, these interactions and their repercussions for the earth system are overwhelming. The environmental impacts of human technology on the limited and by now comparatively small earth system have short- and long-term consequences for our earth system: the term Anthropocene has since been coined for this. Anthropocene describes the action of us humans as an ongoing geological event with massive global impacts in all areas of the (for us) critical zone of the earth. What is fascinating is the scientific discussion on the question of when humans have exerted so much influence on the earth system that we can regard this as a distinct epoch in earth history (Zalasievicz et al. 2024).

The goal of this book is to provide methods with which we can evaluate possible solutions for a future energy technology under the conditions of the Anthropocene and within planetary boundaries. To do so, the environmental impacts of human action must be part of this evaluation. In order to do this, it is necessary to understand them, to be able to estimate and assess them.



Impacts

The impacts of our human actions, which are always actions involving technology, can be subdivided as follows:

1. There is the intended impact, i.e., what was actually planned and envisioned.
2. In addition, there are impacts that, while not desired, are nonetheless foreseen and knowingly accepted (collateral damage such as, e.g., climate warming as a consequence of the use of fossil fuels).
3. There are also direct unintended impacts. These are unforeseen consequences of actions that arise because something was overlooked during planning, because certain interrelationships were not considered, or because interrelationships within the earth system were not known
4. Unintended systemic impacts arise from overlooked interactions between the deliberately altered subsystem and other systems. Very often these possible interactions have not been taken into account or were misjudged.
5. Furthermore, there are future impacts of the intended action that may only come into effect through scale effects. This includes technology lock-in, i.e., the long-term commitment to a particular technology or standard through initial implementations. One example is the 1435-mm standard gauge of railways, which cannot simply be changed today. Also included here are impacts that only arise because something accumulates over long periods of time and thus only gradually becomes noticeable (toxic substances, see Adam 2024), as well as slow responses of complex nonlinear systems (oceanic currents).
6. And finally, there are fundamentally unknown impacts. While all other effects would have been foreseeable with sufficient care in planning, or at least become apparent with increasing knowledge, these effects occur suddenly and unexpectedly. These must not be confused with disavowed interrelationships, which are already included further above.

Perceiving Common societal ways of dealing with unintended environmental impacts, especially the unconsidered, long-term, difficult, or demanding ones, are mostly:

- **Denying:***"No, such a thing does not exist", "That is all scaremongering by crazy fanatics", "99.9% of all scientists and experts are wrong", ...*
- **Ignoring (as a form of denial, DeLay 2024):***"That is not my area of expertise", "That is not my responsibility", "There are truly more important things", "pragmatic and measured", ...*
- **Hoping and believing (as another form of denial, DeLay 2024):***"Someone else will solve it", "It won't be that bad", "I am a technology optimist", "Entrepreneurs will invent something", ...*

  There are a number of current offerings for belief. Many ideologies have imaginative ideas about why the problem does not exist, why it is irrelevant, or why it will disappear on its own if we follow the right prophets.

- **Lack:** Relevant are the lack of imagination (Ghosh 2017), the lack of attention or focused thinking, and the lack of humility.
- **Giving up:** This includes despair, apathy, and cynicism. The age-old theme of the incorrigibility of humans or of youth belongs here, as does a complacency in one's own thinking and acting.
- **Accepting:** Actively and consciously acknowledging the situation and dealing with it. What is meant is coming to act and to carry on, i.e., in a certain sense the normal engineering approach: (i) understand the problem → (ii) develop solution approaches → (iii) define evaluation criteria → (iv) evaluate and select solution approaches → (v) implement → (vi) respond appropriately when things do not work out as planned.

This book focuses on the last approach. It contains many approaches and methods to grasp problems and possible solutions and to make them describable. The emphasis is on evaluation criteria and thus on assessing and comparing possible solutions. Only the last option is based on genuine strength of character, as it requires consciously facing and confronting the truly unpleasant and difficult facts.

2.6 Finding Solutions Methodically

Decisions can be made for very different reasons. As engineers, you learn very specific perspectives and methods to arrive at good decisions. Good engineers possess a certain humility that allows them to prefer working systematically and using these methods. This collection of tools is intended to help analyze solutions in an appropriate and comparable manner. It is meant to help weigh and evaluate solutions against each other. In this way, it aims to contribute to keeping a clear head in difficult situations and finding the way even in the half-dark. The fundamental VDI guideline on design methodology, VDI 2221-1, discusses exactly this and seeks to protect practicing engineers from insufficiently thought-through, foolish or dangerous snap decisions through a methodical approach. As users of the guideline, we are to be forced, through a deliberate slowing down of the decision-making process, to analyze robustly in a first step and only later, and then for comprehensible reasons, to make a decision. The same purpose is served by core elements of management standards such as ISO 9001 or ISO 14001. From the social sciences come methods such as the delta analysis (Bizer/Führ 2014), which also pursue this goal. They all follow the same logic and are directly transferable to one another.

The relevant steps, based on VDI 2221-1 as well as Bizer and Führ, are presented in Table 2.3 (Bizer/Führ 2014). For practical application, it is essential to note that this is not a linear process of sequential execution, but that each step also has repercussions on previous steps and results. Thus, each individual work step can influence

the preceding steps again. In particular, the definition of the goal must be adjusted with the process and the description of the current state must be expanded when new findings or new criteria emerge. The approach requires intellectual flexibility from all involved, goodwill, and often a negotiation process. Other representations of this methodology may name more or fewer steps, but are comparable in essence.

Further prerequisites for this approach are always:

- The group or organization proceeding in this way is honest with itself.
- All goals are clearly named or are artfully co-developed.
- The underlying values are conscious and named.
- The group or organization and its members are capable of learning, discourse, and consensus. This applies in particular to leadership as well.
- The process is open-ended.
- Goals and criteria are adjusted and optimized in the sense of a learning curve. Goals and criteria are not distorted in order to fabricate a preferred solution.

All notes and boundary conditions for wicked problems apply here (see the beginning of Chapter 2).

Table 2.3 The General Approach to Evidence-Based Solution Finding: Solutions Can Be Technical, Organizational, or Behavior-Based

No.	Step	Key question
1	Describe the initial situation	Where do we stand today? What are fixed, predetermined framework conditions and values? What competencies are already available?
2	Describe the goal	Where do we want or need to go? What should our solution be able to do, accomplish, or achieve?
3	Describe the current situation	Why is it the way it is today? What is not good about the current state and should therefore be changed? What is good about the current state and should remain as it is? Which criteria are important and informative enough to assess whether a solution idea or another situation or design is better than the current one?

No.	Step	Key question
4	Describe the difference between the current state and the goal	What needs to be done to achieve the goal? What prevents the actors from pursuing or achieving the goal? What functions must our suitable solution have in order to achieve the goal? How should people use a suitable solution?
5	Find possible solutions	Here, if possible, all relevant possible solutions should be found. At a minimum, however, relevant and fundamentally different options must be found in order to compare them with one another: Which approaches can achieve the goal? Which approaches change the situation in an appropriate way? Which solutions enable the required functions?
6	Evaluate the possible solutions based on the criteria	All possible solutions are compared and evaluated using the same criteria and without bias: Which goals are achieved by which solution? What are the inputs required for the individual solution options? What are the unintended effects of the individual solution options? Which solution, based on current knowledge, offers the best opportunity to achieve the goal without jeopardizing other values?
7	Implementation	The solution option selected in the previous step is implemented.
8	Evaluating the implementation	Accompanying the implementation, the change is to be evaluated: Is the solution as we planned it? Does it function appropriately? Are its other effects tolerable? Do we have undesired effects that we had not thought of beforehand? Do we need to correct or improve the solution? Do we need to abort and start over?
9	Learning	What feedback do the experiences gained have for the organization or society? Are the methods appropriate? Should we change them? Are the fundamental assumptions, including those about the goals, correct?



Making poor decisions

Wicked problems in particular lead to poor decisions in all areas of life. This has several reasons, which ultimately all stem from the effort required:

- There is no correct, unambiguous, or easily accessible solution, but only many more or less poor ways of dealing with the problem.
- It quickly becomes apparent that there is no simple solution, but that the problem requires particularly great attention or resources.
- Nobody already has the necessary resources, experience, knowledge, and competencies to adequately address the problem. Learning is compulsory.
- Every initial analysis already reveals that all proposed solutions have specific disadvantages. Different solution approaches may be disadvantageous for different groups.
- No solution delivers even a satisfactory answer to the more pressing problems right away; it will be necessary to weigh disadvantages against one another.
- Not all consequences of a decision are obvious. Not even after a thorough analysis.
- Therefore, gut decisions, group hysteria, belief systems, charlatans, or magicians can quickly prevail, as they all promise a simple solution without effort and without weighing of interests.

2.7 Decision Spaces

The examples and tasks in this book are designed as if we were allowed to develop a solution to the respective problems. This is not always the case in real life. In everyday life, this situation often presents itself differently. Engineers have a more or less clearly defined decision space within which they are expected to deliver good results. The art here is to make good use of one's own decision space:

- If I am assigned a clearly and completely defined task, it is expected that I make full use of the given decision space: anything else is an indication of decision weakness, lack of capability, or fear. Superiors notice this immediately, and this can close off any opportunity for more responsibility, higher pay, or advancement.
- Often, assigned tasks are not clearly defined. In this case, defining one's own decision space is already part of the necessary clarification of the task. On the one hand, there are boundary conditions that must be adhered to, or certain decisions that must be made by others. This must always be taken into account. On the other hand, the courage to interpret one's own decision space generously is often rewarded, as it demonstrates that I have the big picture in view. This may require either responding flexibly to decisions that were ultimately made elsewhere, or initiating decision-making processes in other places.
- Sometimes it may be necessary to also provide an assessment of problems within one's own organization or of solution approaches by other members of the organi-

zation that was not requested. This is difficult terrain and must be communicated with the necessary sensitivity and flexibility.

- *"Don't ask for permission, ask for forgiveness"* is a motto that in some situations is consciously associated with a personal risk. Asking for permission may take too long, or the answer may initially be fixed and would make one's own action, deemed necessary, impossible. This approach, when applied with the necessary sense of proportion, is a prerequisite for one's own proactive and shaping action.

As citizens, interest representatives, journalists, consultants, non-governmental organizations (NGOs), but also as employees of a company, we often find ourselves in the situation of having to define our own decision space for the benefit of society or the organization. In that case, it is one's own values, one's own competence and knowledge, and one's own motivation that determine this within the framework of the rules of society or the organization.



Attitude influences outcomes

In an organization, it is important to recognize which attitude is fundamentally compatible, which attitude dominates, and which attitudes are not desired. Attitude here refers to a fundamental set of values, expectations, belief systems, but also bases for action that influence decisions without having to be explicitly stated each time.

Classification of attitudes

The attitude with which the observance of planetary boundaries, the transformation of the energy system, or more specifically the handling of greenhouse gases is approached from the perspective of engineers can be classified. Of course, the transitions are fluid and an organization can have different attitudes in different areas (Seager et al. 2012).

Business as usual In this attitude, techno-optimism is at the forefront: the starting point of thinking is the assumption that there will always be a technical solution or that others will solve the problem. More specifically, techno-optimism can be understood as an attitude that already sees the core questions of this book as answered. For techno-optimists, there would always be enough resources, energy would appear when needed, entrepreneurs would deliver solutions at the right time and unconstrained by (natural) law limitations, and infinite growth would represent not a problem but the solution. Complex and wicked problems are in this worldview mostly reduced and simplified to the point where they appear as a purely technical development task for which others are then responsible. From this attitude, it is often already difficult to understand the concept of the wicked problem. Thus, no contribution to solving wicked problems is possible from this stance (Morozov 2013; DeLay 2024).

Systemic approach This is a pragmatic view in which wicked problems are recognized as such. This fundamentally allows interdisciplinary approaches to finding solutions. From this attitude, an approach follows in which previous goals continue to be pursued, but are additionally realized within a sustainability constraint. Financial aspects thus continue to be the drivers of development, with the boundary condition

that additional regulatory requirements are now to be met by the sought solution. Green Growth falls into this category.

A somewhat more far-reaching second variant consists of methods within the framework of a Triple Bottom Line (as a three-pillar model: profit, people, planet). Within this framework, in addition to purely financial drivers, social aspects and aspects of interaction with the (natural) environment are also included. At its core, this involves a negotiation process between these three aspects, which can be structured, for example, in the form of a risk assessment. The result is products that are manufactured or used more efficiently or are less harmful with regard to their environmental impact, and which individually can indeed contribute to sustainable development goals, as they have less harmful environmental impacts. Scale effects, which are not taken into account in the analysis, can then reduce or even reverse this contribution. Even if Triple Bottom Line will not be sufficient to solve the major problems of sustainable development (see Chapter 8), it is nonetheless a common and attractive attitude for companies today, from which at least an attempt is made to provide one's own serious and relevant contribution.

Sustainable Engineering Science This approach is characterized by a fundamental skepticism toward purely technical solutions. This skepticism relates in particular to elaborate, material- or energy-intensive solution proposals. Transformation to sustainable development is fundamentally understood as a wicked problem, for which purely technical solutions can rarely exist. At the center of engagement with wicked problems are feedback effects and scale effects.

The methods in this book support a systemic approach and sustainable engineering science.

Where do I want to work?

I can choose the organization in which I want to work based on its attitude. Attempting to implement a fundamentally different attitude within an organization is very difficult, time-consuming, and often fails. In a company, it is the task of top management to develop the organization's attitude and then also enforce it internally (ISO 14001). I can help company management with this goal. However, a change in attitude cannot be enforced against management without at least considering a change in that management.

Compliance A typical and important example is the question of how an organization deals with legal requirements. The attitude toward this is understood by everyone within the organization, even if this attitude is not always clearly formulated in writing or the official statement on it may differ. Compliance means adhering to existing legal requirements. For organizations, compliance in this sense involves considerable effort, as the current status must be regularly researched. This must be communicated within the organization; when changes occur, procedures, processes, and products must be adapted and, if necessary, extensively modified, and compliance must be verified internally. Compliance is one of the essential elements of risk management within an organization. Compliance is essentially law-abidingness and thus self-evident, but this can be viewed and presented differently within an organization. It is

then my personal decision whether I want to be part of such an organization and am willing to bear the associated personal risks.

2.8 Risk

Dealing with risks is a high art. In many areas of life, risks can be relevant or significant. Risks and thus the sensible and necessary approach differ for different areas or sectors. Companies must know their business risks and develop appropriate strategies for dealing with them. Insurance companies must additionally identify, assess, and quantify the risks of their customers. States must, within the framework of public services, recognize the risks of their citizens and determine the appropriate way to deal with them. In all cases, complex trade-offs between different types of information, legal interests, and claims are necessary.

Organizations ISO 31000 describes the method of risk assessment for risks affecting an organization. It is therefore the perspective of the organization looking outward and inward that is considered here. This standard provides a good introduction to methods for dealing with risks, and the concept of risk used there is relevant here.



Term risk

A helpful definition of the term risk according to ISO 31000 is as follows:

"Effect of uncertainty on objectives"

→ *An effect is a deviation from expectations – in a positive and/or negative direction*

→ *The objectives can cover various aspects (e.g., finance, health and safety, and environment) and apply at different levels (e.g., strategic, organization-wide, project-, product-, and process-related objectives)*

→ *Risks are often characterized by reference to potential events and consequences or a combination thereof. Risks are often described in terms of the consequences of an event (including changes in circumstances) in combination with the likelihood of its occurrence*

→ *Uncertainty is the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence, or likelihood"*

A different perspective on the concept of risk and forms of risk reduction is brought by product safety, as fundamentally introduced in ISO 12100, already through the definition. Here, a risk is the

"combination of the probability of occurrence of harm and the severity of that harm."

This standard refers very specifically to the placing on the market of products for which the respective CE directives apply within the EU. The fundamental method for risk reduction for products is presented in ISO 12100. This concerns concrete physical risks to persons and, where applicable, to domestic animals that arise directly from prod-

ucts. Long-term, systemic, psychological, or generally societal risks are explicitly not covered.

Management The goal of risk management is to develop an orderly and systematic procedure for dealing with risks and then to apply it consistently. The resulting risk assessment and ultimately risk reduction aims to identify all relevant risks and to define measures by which a possible impact, in particular a possible harm, can be limited to an acceptable level.

A risk assessment is at least in the European legal system, in which the precautionary principle applies, fundamentally necessary before a measure is taken that may contain risks. As an important requirement for risk management and thus for risk assessment, ISO 31000 states:

- The goal is to protect or create value in all areas of life. Specifically mentioned are human health and safety, compliance with legal and regulatory requirements (compliance), public acceptance of measures or products, protection of the environment from environmental impacts, ensuring product quality, aspects of project management, and good governance.
- Risk management should be an integral part of all decision-making processes and part of the decision-making itself.
- Risk management explicitly addresses uncertainty, i.e., uncertainty must not be a reason to neglect an aspect, but is first and foremost an indicator of a relevant aspect.
- The method is systematic, structured, and timely, i.e., scientific. It is based on currently available information. It uses orderly procedures where possible. The purpose of the standard is thus to effectively prevent naivety, belief, intellectual laziness, entrenched thinking patterns, excessive optimism, and other obstacles to an evidence-based engagement with one's own objectives and uncertainties.
- Each organization must find its own procedures and structures that adequately cover its risk portfolio.

Time frame A fundamentally difficult question is the time frame over which risks are considered. Here, any legal requirements are only one aspect. A very long planning horizon is necessary especially for governments. For long-term companies in the area of raw material extraction or basic industries, planning horizons of 30 years are rather common. A cost-benefit perspective is often used (see Chapter 6). This implicitly uses a time frame, but does not answer the underlying question, merely shifting it.

Methods The general method for dealing with risks consists of the steps indicated in Table 2.4. Independently of this, the following considerations are relevant for establishing the criteria for the assessment of risks:

- Are the causes of change one-time or long-term, unexpected or systemic?