

Dr. J.M.H. Huynen

# Blue battery for green energy

**Underground pumped hydro storage**

- energy transition •
- variability wind and sun •
- storage technologies •
- underground potential •

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PHONE +31 15 2782124  
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# Preface

I have sincere concerns that modern civilization is on its way to destroy our beautiful blue and green planet. Already, the quality of life is endangered by the extreme exploitation of our earth.

It is the obligation of everyone in this world to contribute to a change. We all share the responsibility of bringing about a cleaner environment and a more sustainable society, in order to preserve this planet for future generations, our children and grandchildren.

I have deep respect for the pioneers who initiate changes. Without them, we wouldn't have such promising technologies as wind and solar energy, electric cars, and smart grids. At the same time, questions haunt me. Such as how to power a society that never sleeps when there is no wind or sun. Or how sustainable and durable batteries in electric cars really are. And how batteries could provide economically substantial carbon-free storage power to the electricity grid in the long run. The answers to these questions will help the transition towards a more sustainable way of life, which is my first and foremost motivation for writing this monograph.

The second driver is the observation that there is insufficient awareness in scientific and engineering circles of the capabilities of pumped hydro storage. There is hardly any mention of its enabling force in the transition to a sustainable decarbonized electricity supply. It is surprising that the Dutch community of energy specialists "Watt Connects", with more than 1,000 members, is ignorant of the potential of hydro storage.

My academic fire was kindled by the eminent scientists Professor Gert Jan Kramer (Utrecht University) and Professor Han Vrijling (Delft University of Technology). Both inspired me years ago to document decades of research and development of an underground large-scale hydro storage project.

My academic motivation is not just to obtain a PhD degree. I earned one from the very same *alma mater* some 45 years ago. But, by writing about this challenging and inspiring subject, I hope to bring the realization of this innovative project closer. As this monograph shows, its technology is proven, its economics is sound and its funding is within reach. Underground pumped hydro storage is not only a flatland solution for a flat country. It is also a smart way of using the underground to preserve the surface of our dear earth – anywhere in the world.

# Acknowledgements

First and foremost, I am deeply indebted to my supervisors, Professor Gert Jan Kramer and Professor Han Vrijling. Without their stimulating assistance and scientific guidance, this monograph would not have seen the light of day. Gert Jan, as a complete, sharp-witted scientist, has had the patience to explain complex processes and correct me where and when necessary. I owe him many thanks for sharing his keen insights. Also with Han – a highly experienced engineer and at the same time a fine economist – I had the benefit of a long-term training with a wealth of practical engineering advice. I want to express my deep feelings of gratitude to both.

From 1985 onwards, I had the privilege of working on the OPAC project in three consecutive study groups. I had a personal interest in this project, since I was at that time vice president of a major Belgian electromechanical manufacturer of pumped hydro installations, ACEC (Ateliers de Construction Électrique de Charleroi). In that period, Hans de Haan, project manager of OPAC and later CEO of Haskoning, introduced me to the secrets of pumped storage technology. I owe him my gratitude for his willingness to share his extensive civil engineering experience with me. The OPAC group consisted initially of Haskoning, KVS (Koninklijke Volkert Stevin), Aveco engineers, TH Delft (now Delft University of Technology), and Sogecom. A large team of specialized Dutch and German engineers, geologists and other specialists designed and developed the OPAC plan, which was coordinated by NEOM (Netherlands Energy Development Agency) and commissioned by the Ministry of Economic Affairs.

Of all who contributed in these early days of the plan, I would like to especially mention two visionaries. The Queen's Commissioner Sjeng Kremers and members of his administration visited the 1,800 MW PHS power plant in Dinorwig (Wales) and became convinced that OPAC could offer a unique opportunity for a bright energy future, replacing the lost prosperity of the then closed coal mines in South Limburg. Also the managing director of PLEM (Limburg Provincial Electricity Company) Frans van Eyndhoven, who passed away all too

early, shared his expert vision as an electrical engineer. He carried out the first calculations for the revenue model.

In spite of all these efforts, Dutch Parliament decided in 1989 to abandon OPAC. The completed files about the design and construction of our energy storage plan consequently disappeared into archives, having lost their immediate relevance.

Only later did the contours of a fundamental change in power supply become visible, with an increasing role for sustainable sources such as wind and sun. In 2006, Hans de Haan (Royal Haskoning) and I took up the initiative to present the plans in an adapted form to the Ministry of Economic Affairs. This time, the plan was supported by the Queen's Commissioner Léon Frissen and Bert Kersten, member of the Provincial Executive. They deserve praise for their inspiring, sustained and public support. The then re-established study group consisted of Royal Haskoning, Hans de Haan, Leo Visser, Frank Wetzels, Lood van Velsen, along with Twan Arts and Wouter Muller of Sogecom, and Ruut Schalijs, former Director of Corporate Development & Strategy for NUON. The provincial authorities assigned Professor Han Vrijling as an external advisor for his civil engineering expertise. This was the start of an inspiring relationship, which deepened my knowledge of the intricacies of this complex subject and eventually led to this monograph.

Moreover, the Province of Limburg supported the establishment of an independent foundation chaired by Jos Schneiders, with Jan Mans, Hendrik Tent, Ton Versteegh and Jacques van Geel as members. The province commissioned the chairman to complete a feasibility study of O-PAC. I am much indebted to them all. As geology is a crucial part of the O-PAC project, it was a great help to be able to deepen my knowledge of the geostructural aspects in cooperation with Professors Peter Kukla, Janos Urai and Christoph Hilgers (all from RWTH Aachen University), and Professor Christoph Clauser (E.ON Energy Research Center). Professor Hans Maks (Maastricht University) and Maurice Oude Wansink (OWP Research) provided valuable insights regarding the economic and Euregional effects. The partnership with Hochtief led to an intensive cooperation with Professor Christof Gipperich, whom I owe much gratitude during these difficult years of changing circumstances.

In the Dutch parliamentary debates on the liberalization of energy markets, O-PAC again rose to prominence on the agenda. Thanks to

MP Jos Hessels (CDA), a motion was adopted in 2008, supported by a broad majority, in which TSO TenneT is advised to facilitate large-scale storage.

DSM's chair Feike Sijbesma is a frontrunner of the industrial transition to sustainability. His inspiring and active support, by making DSM locations available, is highly appreciated.

In spite of the efforts of the King's Commissioner Theo Bovens and member of the Provincial Executive Patrick van der Broeck, political changes within the administration of the Province of Limburg ended the cooperation, and hence the plans had to be suspended again.

However, new challenges come to the fore, as recent national policy measures triggered further progress towards renewable energy. This new momentum led to the third incarnation of the project. The new O-PAC development team consists of Ruud Deckers, Twan Arts, Edwin Brouwers, Ruut Schalijs and Guido Custers. The team collaborates with Wolfram Kagerer and other tunnel construction specialists from Müller + Hereth Ingenieurbüro für Tunnel- und Felsbau. One of their main tasks was to update the construction costs. These calculations are essential for attracting investors, and their efforts are the reason for me to extend my warmest thanks to all involved.

I appreciated the discussions and the help of Peter Martens, Roland Starmans, Leo Holwerda, and Bert Mulders of NIA (Netherlands Investment Agency). I also thank general director of Sustainability and Environment Peter Struik of Rijkswaterstaat, Ministry of Infrastructure and Environment, and his team for the open-minded discussions about large-scale storage technology.

In the last and probably most decisive phase, I enjoyed the professional discussions with Lucas Pollemans and Frans Nillesen, both from Netherlands Enterprise Agency, and Mart van Bracht and Ed Buddenbaum, both from Topsector Energy, as well as geologist Serge van Gessel from TNO, Frits van der Velde from VEMW, Mark van Stiphout from the Directorate-General for Energy (European Commission), Hans van der Spek from FME, Frits de Groot from VNO and Meindert Smallegenbroek from the Ministry of Economic Affairs and Climate Policy.

During recent years, a great number of persons have sympathized with O-PAC out of various considerations, and foremost among these has been investment specialist Gert Jan Staal. We

also experienced support from Belgium, from energy engineers Patrick Lafontaine and Jacques Schittekat. From Limburg, support was received from leading organizations and persons such as Jan Zuidam, Boy Litjens, Frans Weekers (EBRD), Paul Hamm, Gosse Boxhoorn, Koos van Haasteren, Roy op het Veld, Jacques D'Elfant, and last but not least, Professor Luc Soete, former Rector of Maastricht University. I am very grateful for their enthusiasm, which I hope will result in the realization of this ambitious project. Over the years, a great many other people shared their ideas with me; I apologize that I cannot mention them all. Be assured that I appreciated all contributions and ideas, big and small.

Having been a general aviation pilot for some 40 years, I know the concentration it takes to prepare an aircraft for landing. It is teamwork, but the captain takes the controls and responsibility for a safe landing. This metaphor reminds me how I feel in the final phase of this thesis. In my imaginary cockpit, the first pilot is Twan Arts and the flight engineer is Leendert Corbijn. Because it is a long-haul flight, there is a backup crew consisting of Ruud Deckers, Ruut Schalijs and Edwin Brouwers, whilst the technical support is provided by Bram Vermeer, Joezio Skrobiszewski and Brian Wright. They all contributed to a good flight and a safe landing. Moreover, a pleasant stay on board is important, which is in the hands of our purser Marjan Huynen, who contributed more to a soft landing than anyone can imagine.

Finally, every flight needs proper guidance, therefore the survey on the tower is secured by the flight controllers Gert Jan Kramer and Han Vrijling.

Thanks for flying with me.



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# 1 Introduction

This monograph discusses the technical and economic potential of underground pumped hydro storage (U-PHS) for the transition to a low-carbon energy system.

Energy storage will play a key role in enabling the further deployment of variable renewable power sources, such as electricity from wind and sun. U-PHS has been proposed for many decades and it is, as this thesis will make clear, a valuable addition to the available energy storage technologies. It is remarkable how infrequently U-PHS is mentioned in the literature. This study intends to remedy this and give U-PHS the place it deserves.

This monograph illustrates the potential of U-PHS through a Dutch case study (in Part Two). Therefore, special emphasis is on the Dutch energy transition and its European context.

## 1.1 Elevations in a flat country

The eventual transition from fossil fuels to a carbon-neutral power system is widely seen as a necessity. This insight came only gradually and the arguments for it have shifted over time. From the middle of the 20th century, the depletion of natural resources, pollution and population growth were discussed, as marked by the report “The Limits to Growth” (Meadows, et al., 1972). Though not all conclusions of this study were accepted at the time, it contributed to the awareness of the need for drastic changes in human behaviour. The effects of fossil fuels on the global climate became gradually clear during the subsequent decades.

From 1988 onwards, the IPCC (Intergovernmental Panel on Climate Change) has provided scientific guidance on climate change and its environmental, economic and societal impacts. Based on its findings, the UNFCCC (United Nations Framework Convention on Climate Change) was established in 1992 with the objective of the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (United Nations, 1992).