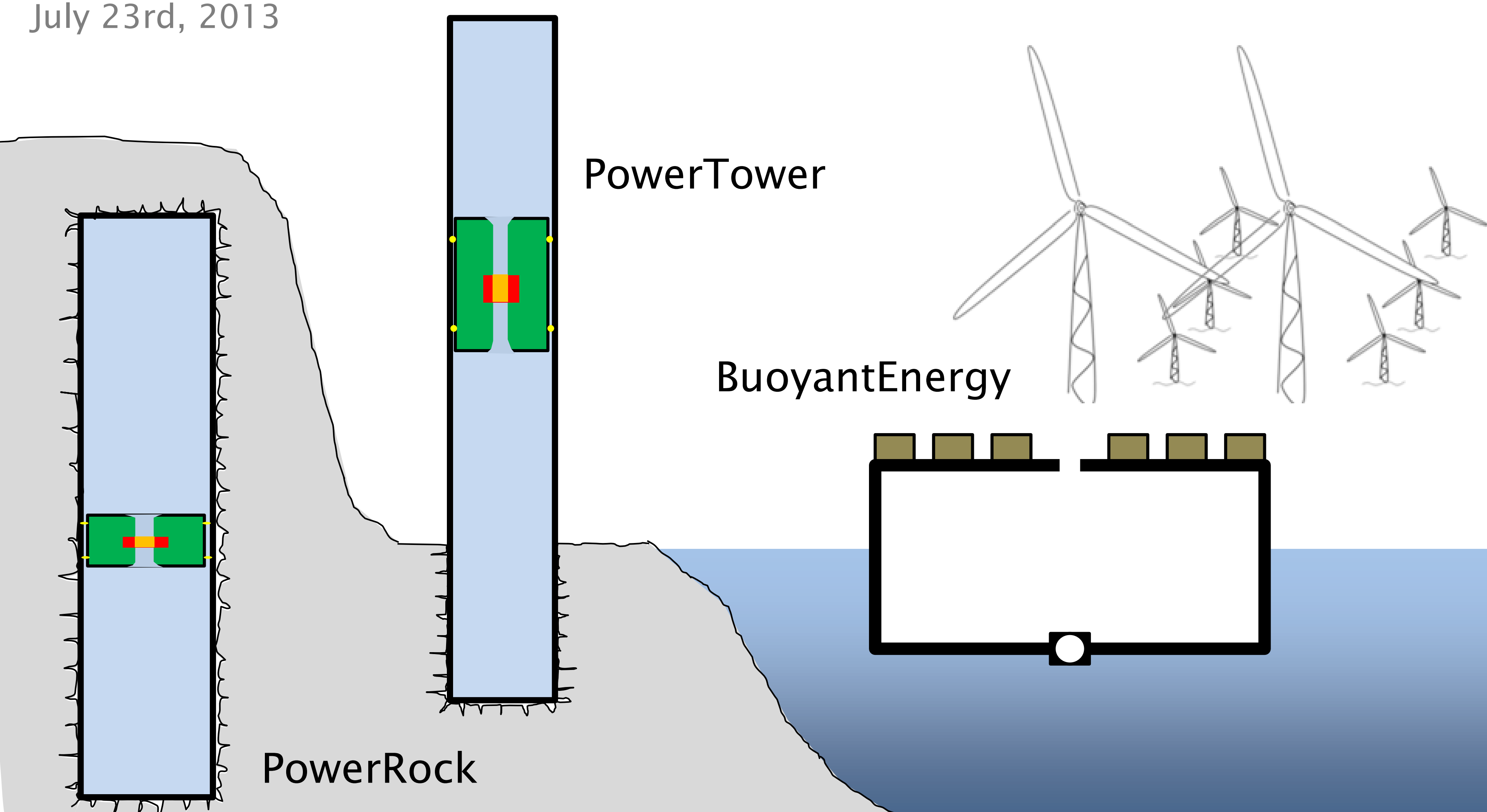
University of Innsbruck
Hydraulic Engineering Dept.

Decentralized Offshore Energy Storage for the future European Power Grid

Robert KLAR, Markus AUFLEGER

July 23rd, 2013



PowerTower

BuoyantEnergy

PowerRock

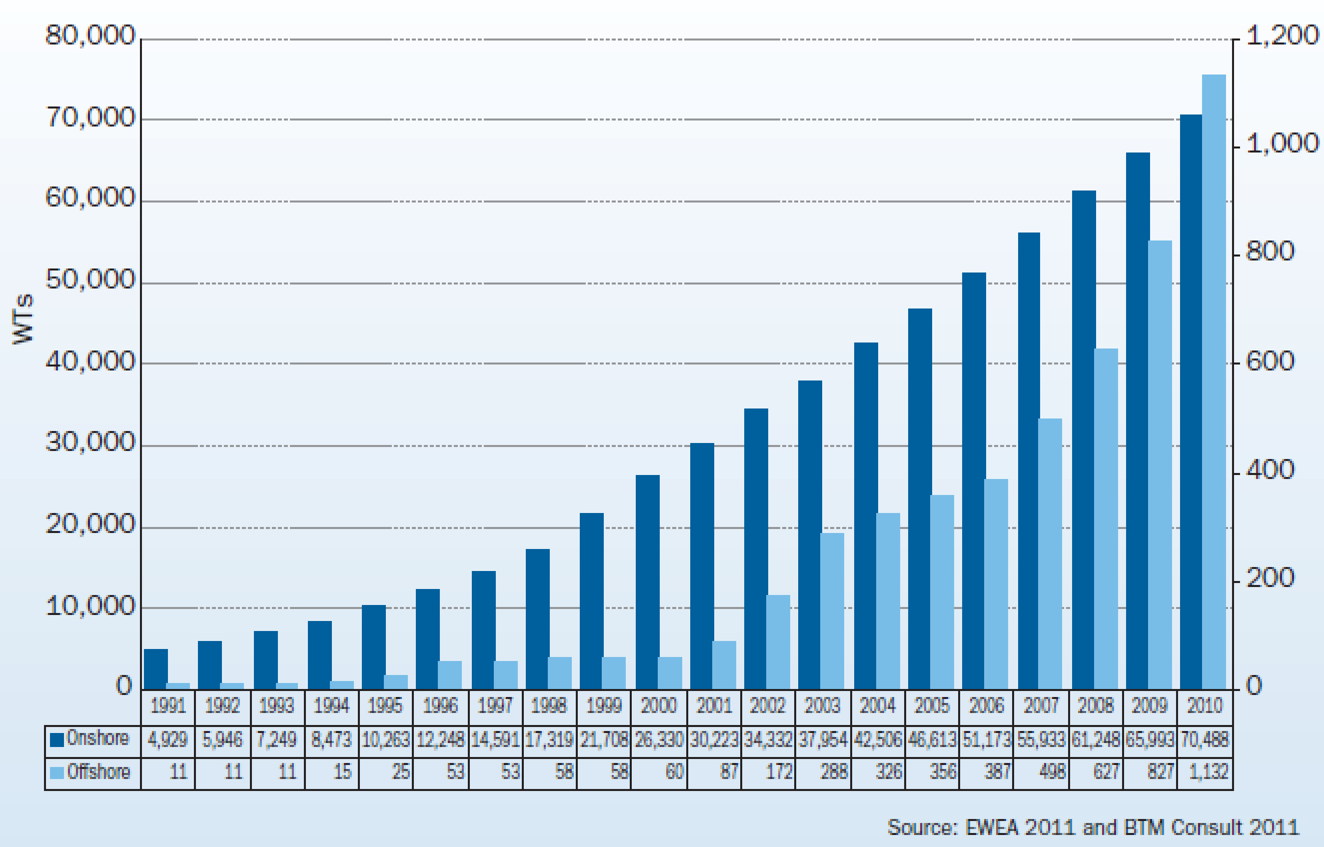
MOTIVATION

What is so interesting about *decentralized offshore* energy storage?

Expansion of Wind Energy

Total Number of Wind Turbines in the EU (1991 – 2010)

(*onshore* – left axis; *offshore* – right axis)

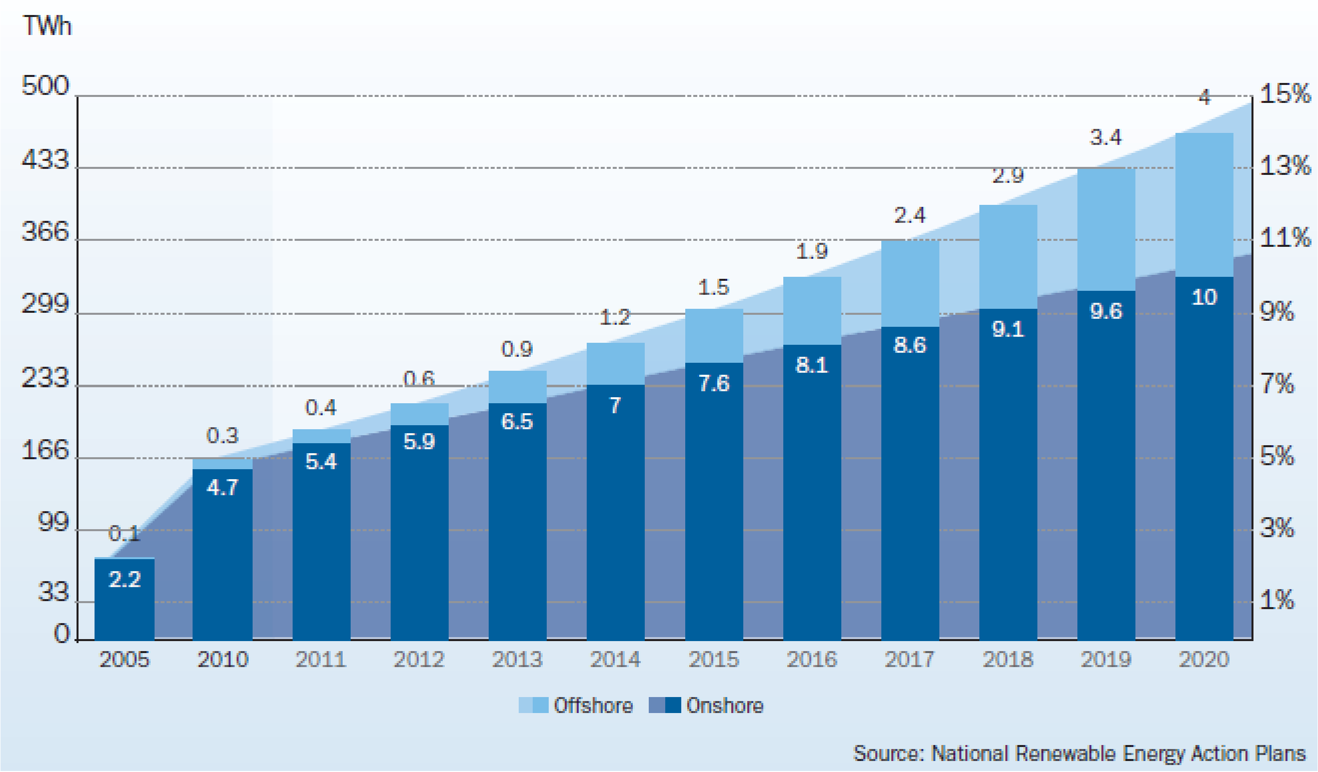


	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
■ Onshore	4,929	5,946	7,249	8,473	10,263	12,248	14,591	17,319	21,708	26,330	30,223	34,332	37,954	42,506	46,613	51,173	55,933	61,248	65,993	70,488
■ Offshore	11	11	11	15	25	53	53	58	58	60	87	172	288	326	356	387	498	627	827	1,132

Source: EWEA 2011 and BTM Consult 2011

Expansion of Wind Energy

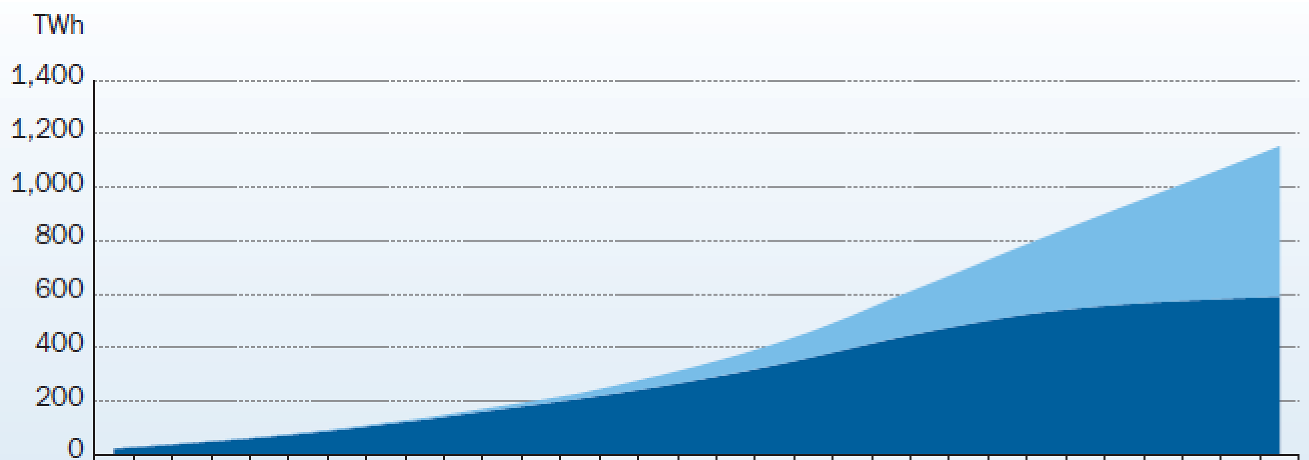
Estimated Energy Production from *onshore* and *offshore* Wind Energy Plants according to the NREAPs (National Renewable Energy Action Plans)



Source: National Renewable Energy Action Plans

Expansion of Wind Energy

Estimated Energy Production from *Onshore* und *Offshore* Wind Energy Plants in the EU (2000–2030)



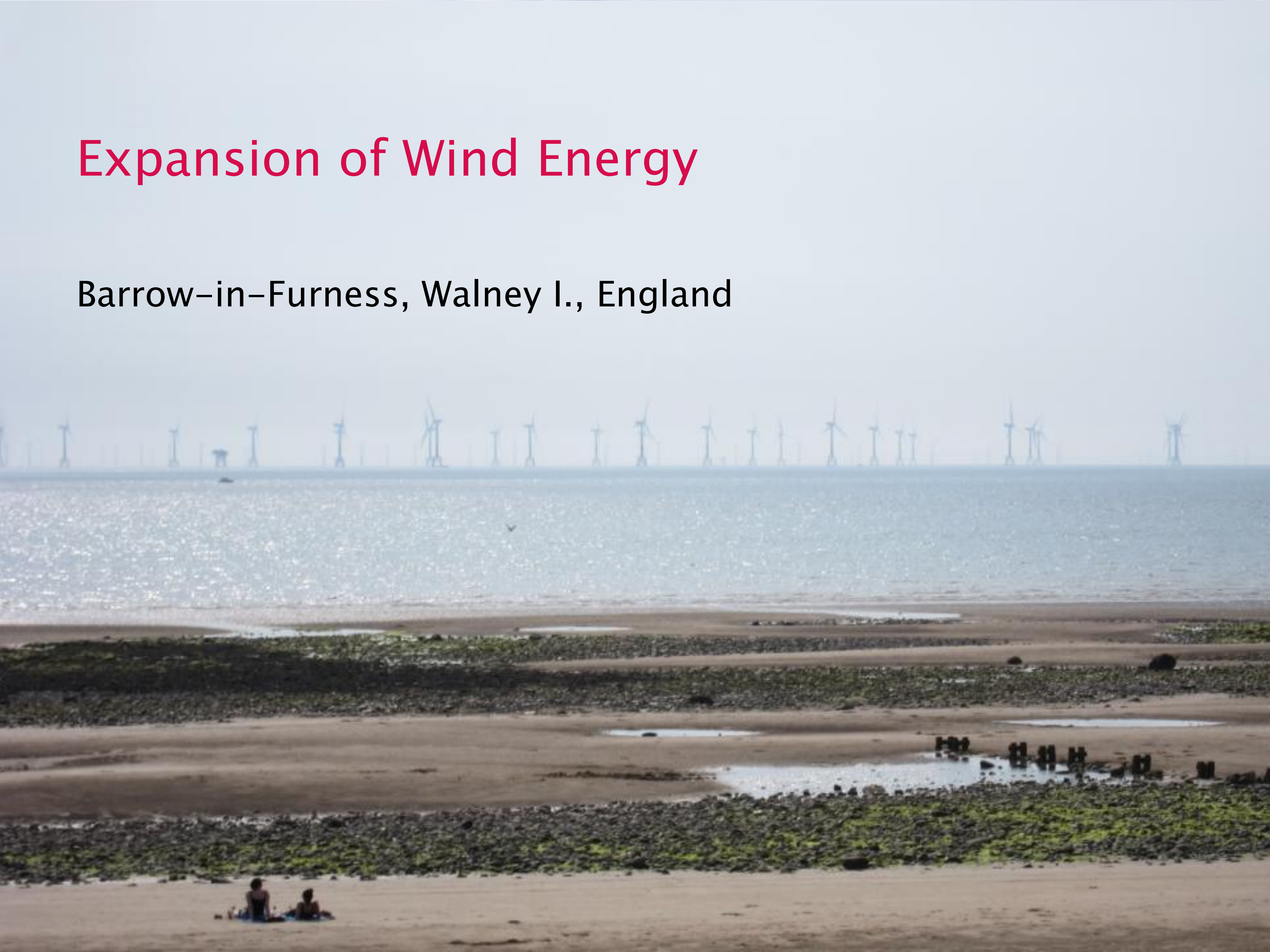
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
🟦 Offshore	0	0	1	2	2	2	3	4	5	7	11	14	19	29	40	51
🟦 Onshore	22	32	44	55	67	80	96	115	131	152	171	190	209	231	254	279
Total	23	32	44	57	69	83	100	118	136	159	182	204	229	260	294	330

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
🟦 Offshore	63	78	97	120	148	177	209	244	281	322	366	412	461	511	562
🟦 Onshore	306	335	366	399	433	462	489	514	534	550	562	571	579	586	591
Total	369	413	463	519	581	639	698	757	816	873	928	983	1,040	1,096	1,154

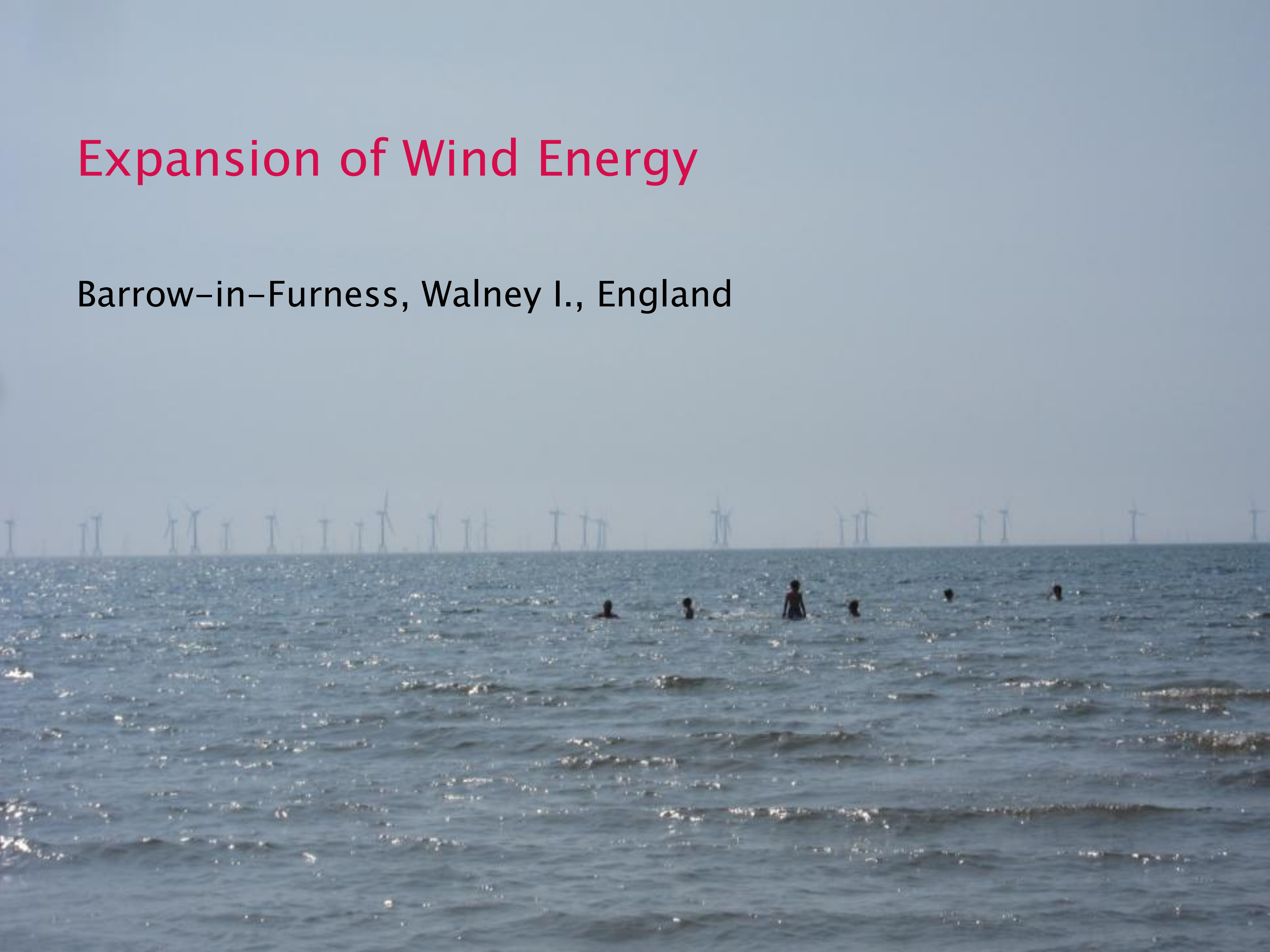
Source: EWEA 2011

Expansion of Wind Energy

Barrow-in-Furness, Walney I., England



Expansion of Wind Energy



Barrow-in-Furness, Walney I., England

Compensation: Energy Demand ⇔ Energy Supply

DIE ZEIT 8.September 2011

Windkraft in die Kaverne

Die Umwandlung überschüssigen Ökostroms in Gas könnte das Speicherproblem lösen

VON CHRISTOPH M. SCHWARZER

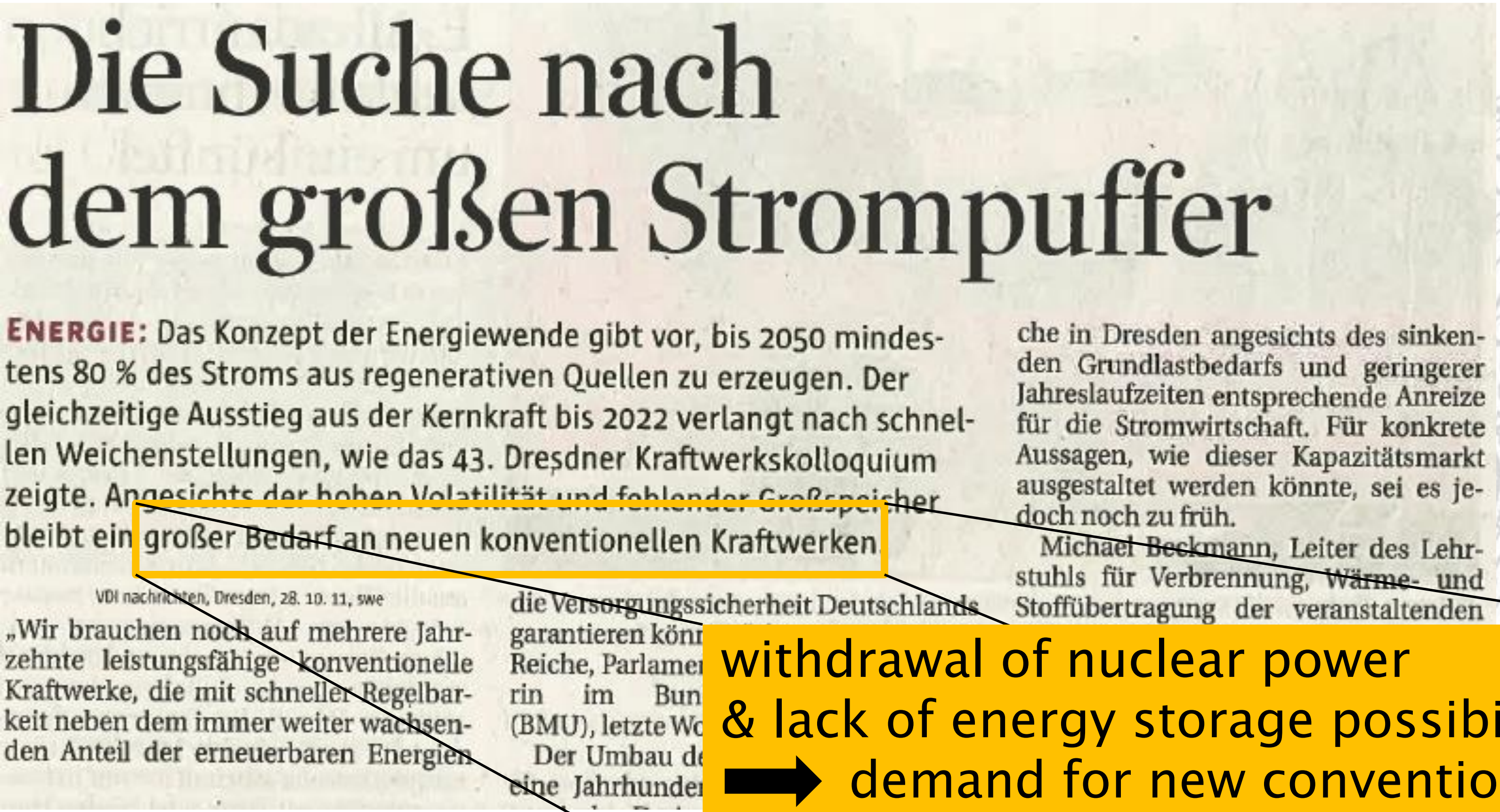
Stillstand bei sieben Beaufort. Die langen Rotorblätter der Windkraftanlage verharren starr trotz dieser frischer Brise. Weil jede weitere Kilowattstunde die Stabilität des Stromnetzes gefährden würde, wurde dieses sichtbare Symbol der Energiewende zwangsweise abgeschaltet. Ein widersinniger Zustand, der immer häufiger eintritt: Vergangenes Jahr gingen laut Bundesnetzagentur fast 74 Millionen Kilowattstunden so verloren. Einzelne Betreiber im Norden Schleswig-Holsteins mussten ein Viertel ihrer Gesamtproduktion abschreiben. »Ausfallarbeit« heißt das euphemistisch im Behördendeutsch. Nach Paragraf 12 des Erneuerbare-Energien-Gesetzes (EEG) wurden dafür gut sechs Millionen Euro Entschädigung gezahlt, Tendenz steigend.

Was fehlt, ist ein Speicher für den Strom. Einer, der so groß ist, dass er die Republik über Wochen versorgen kann, der überall verfügbar und kostengünstig ist. »Wir haben ihn schon«, sagt Stephan Rieke von Solar Fuel Technology, »Deutschlands größter Speicher ist das Erdgasnetz.« Statt wie bisher Erdgas in der Turbine eines Kraftwerks zu ver-

74 Million kWh wasted in one year

Compensation: Energy Demand ⇔ Energy Supply

VDI Nachrichten, 28.Oktober 2011



Die Suche nach dem großen Strompuffer

ENERGIE: Das Konzept der Energiewende gibt vor, bis 2050 mindestens 80 % des Stroms aus regenerativen Quellen zu erzeugen. Der gleichzeitige Ausstieg aus der Kernkraft bis 2022 verlangt nach schnellen Weichenstellungen, wie das 43. Dresdner Kraftwerkskolloquium zeigte. Angesichts der hohen Volatilität und fehlender Großspeicher bleibt ein großer Bedarf an neuen konventionellen Kraftwerken.

VDI nachrichten, Dresden, 28. 10. 11, swe

„Wir brauchen noch auf mehrere Jahrzehnte leistungsfähige konventionelle Kraftwerke, die mit schneller Regelbarkeit neben dem immer weiter wachsenden Anteil der erneuerbaren Energien

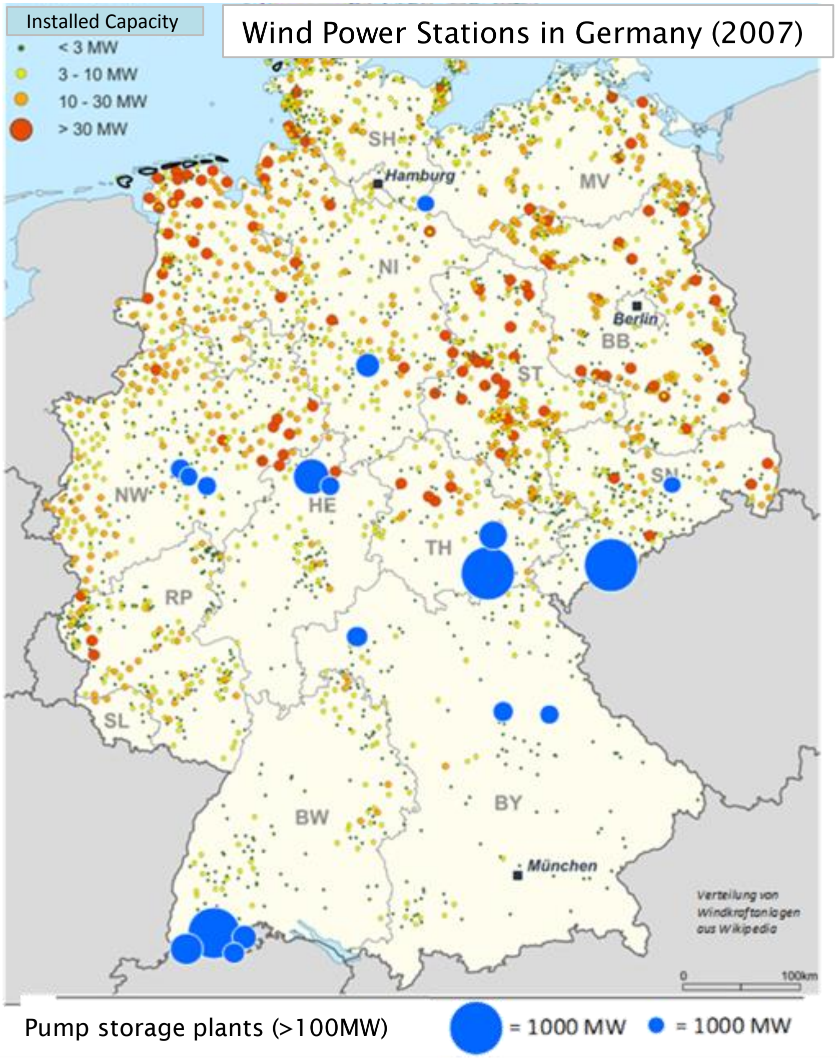
die Versorgungssicherheit Deutschlands
garantieren könn
Reiche, Parlamen
rin im Bun
(BMU), letzte Wo
Der Umbau de
eine Jahrhunder

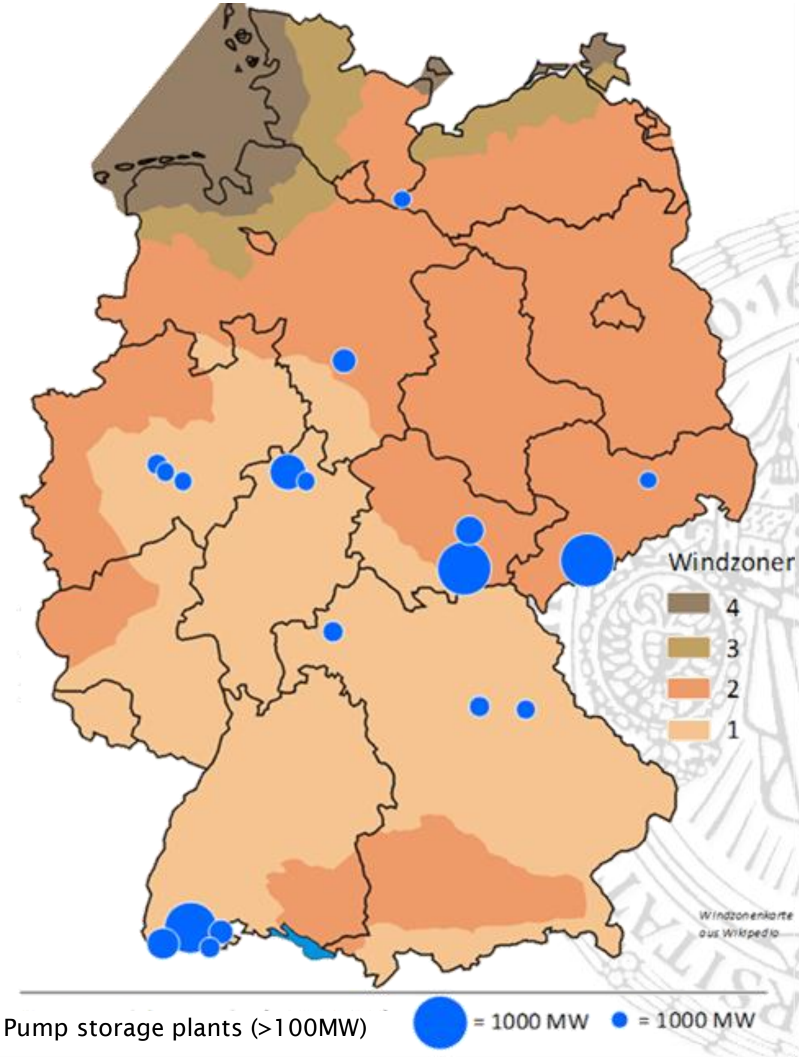
che in Dresden angesichts des sinkenden Grundlastbedarfs und geringerer Jahreslaufzeiten entsprechende Anreize für die Stromwirtschaft. Für konkrete Aussagen, wie dieser Kapazitätsmarkt ausgestaltet werden könnte, sei es jedoch noch zu früh.

Michael Beckmann, Leiter des Lehrstuhls für Verbrennung, Wärme- und Stoffübertragung der veranstaltenden

withdrawal of nuclear power
& lack of energy storage possibilities
➡ demand for new conventional power plants

Compensation: Energy Demand ⇔ Energy Supply

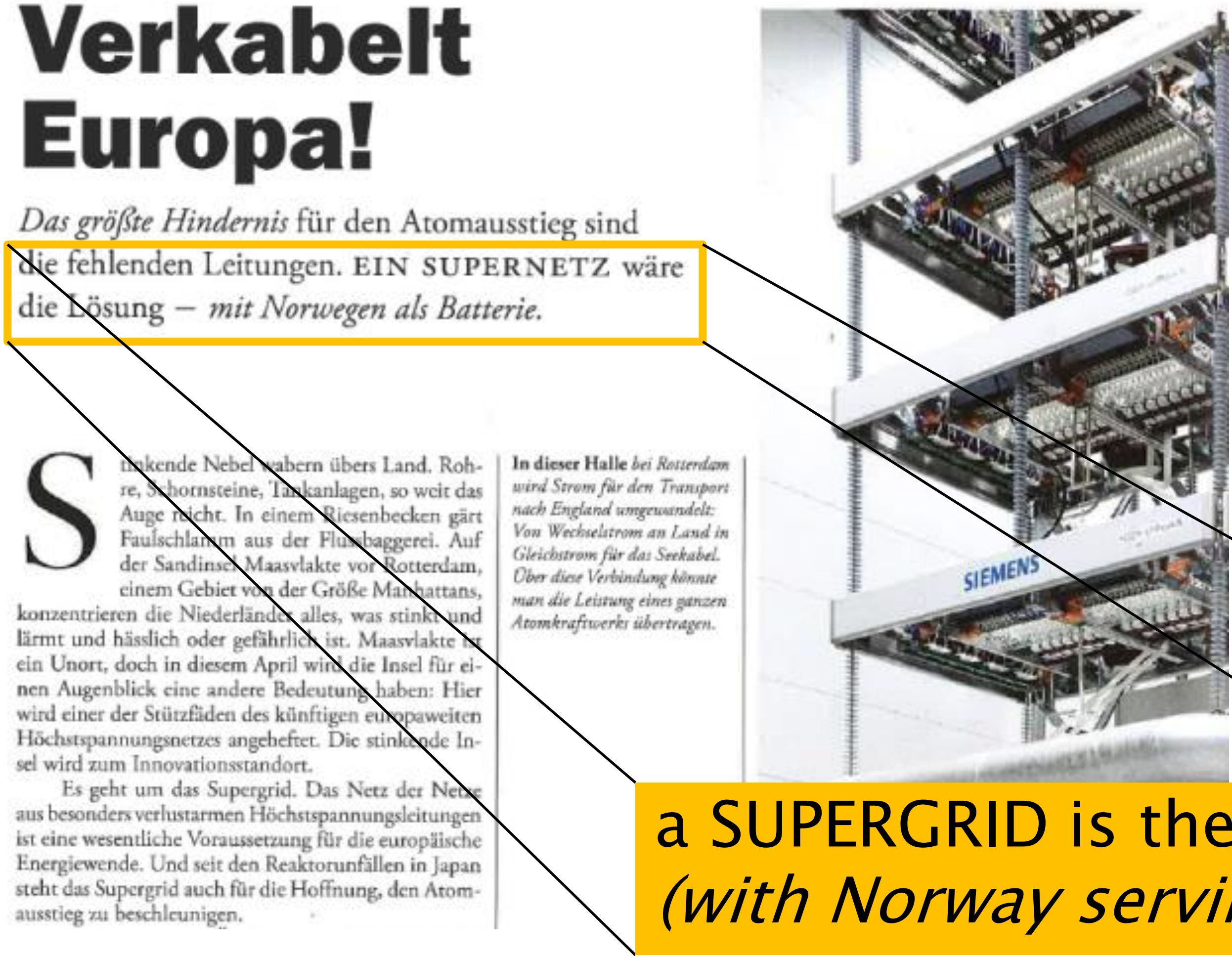




Source: Aufleger, Markus (2008): Strom fließt – Wasserkraft 2020, Bauingenieur, Band 83, Juli/August 2008

Compensation: Energy Demand ⇔ Energy Supply

DIE ZEIT WISSEN – April/Mai 2011



Verkabelt Europa!

Das größte Hindernis für den Atomausstieg sind die fehlenden Leitungen. EIN SUPERNETZ wäre die Lösung – *mit Norwegen als Batterie.*

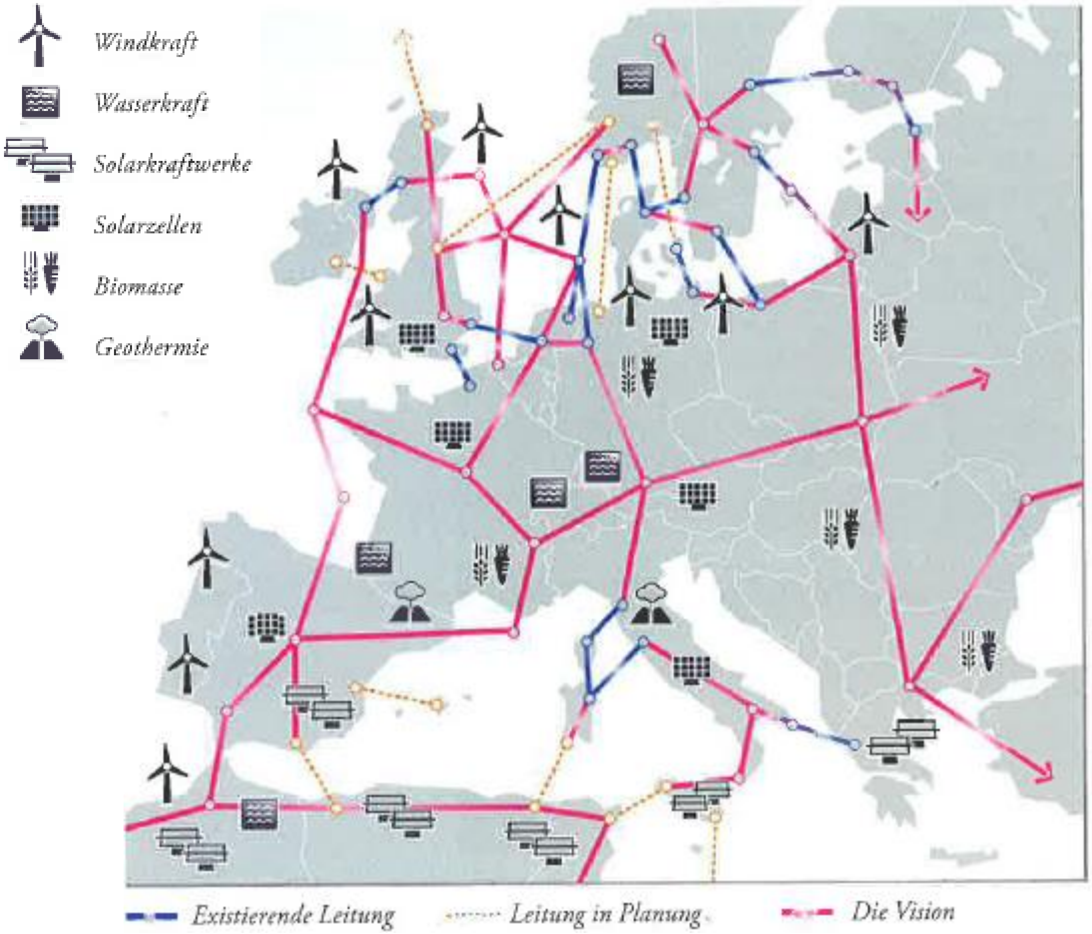
Stinkende Nebel wabern übers Land. Rohre, Schornsteine, Tankanlagen, so weit das Auge reicht. In einem Riesenbecken gärt Faulschlamm aus der Flussbaggerei. Auf der Sandinsel Maasvlakte vor Rotterdam, einem Gebiet von der Größe Manhattans, konzentrieren die Niederländer alles, was stinkt und lärmt und hässlich oder gefährlich ist. Maasvlakte ist ein Unort, doch in diesem April wird die Insel für einen Augenblick eine andere Bedeutung haben: Hier wird einer der Stützfäden des künftigen europaweiten Höchstspannungsnetzes angeheftet. Die stinkende Insel wird zum Innovationsstandort.

Es geht um das Supergrid. Das Netz der Netze aus besonders verlustarmen Höchstspannungsleitungen ist eine wesentliche Voraussetzung für die europäische Energiewende. Und seit den Reaktorunfällen in Japan steht das Supergrid auch für die Hoffnung, den Atomausstieg zu beschleunigen.

In dieser Halle *bei Rotterdam wird Strom für den Transport nach England umgewandelt: Von Wechselstrom an Land in Gleichstrom für das Seekabel. Über diese Verbindung könnte man die Leistung eines ganzen Atomkraftwerks übertragen.*

a SUPERGRID is the solution?
(with Norway serving as battery)

SUPERGRID: High Voltage DC Transmission



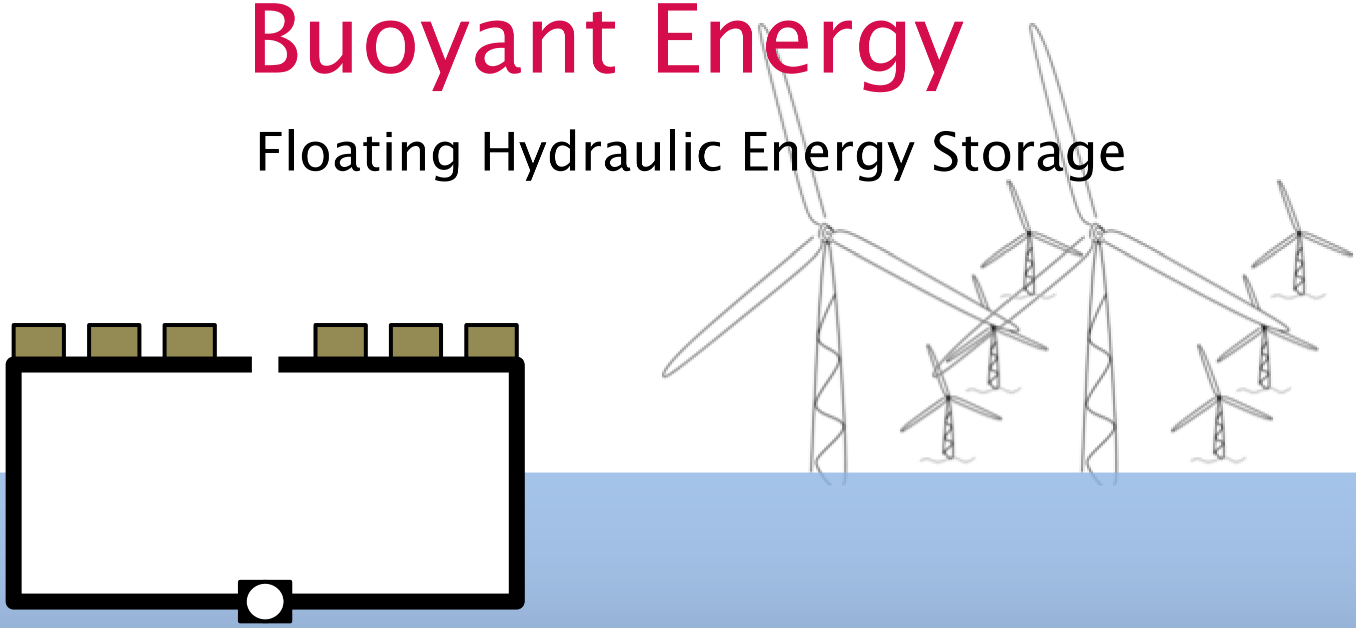
Source: Die Zeit – Wissen, Mai 2011, Burkhard Straßmann

- 800 to1100 kV Voltage
- Germany alone still needs 3600 km of high-voltage power lines
- Estimated costs: 10 Billion Euros (Germany)

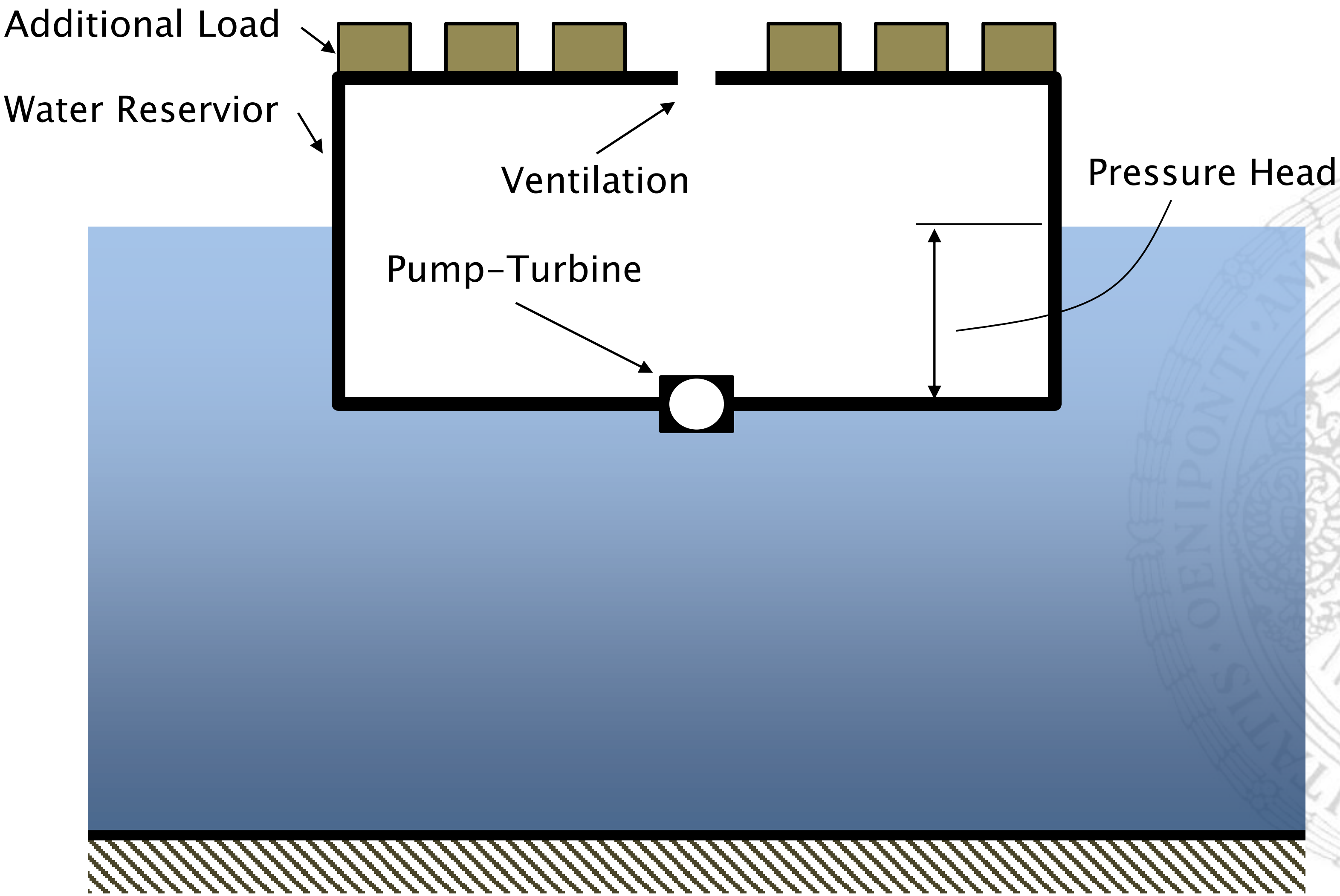
➡ the SUPERGRID solution is cost-intensive and requires extensive authorization procedures!

Buoyant Energy

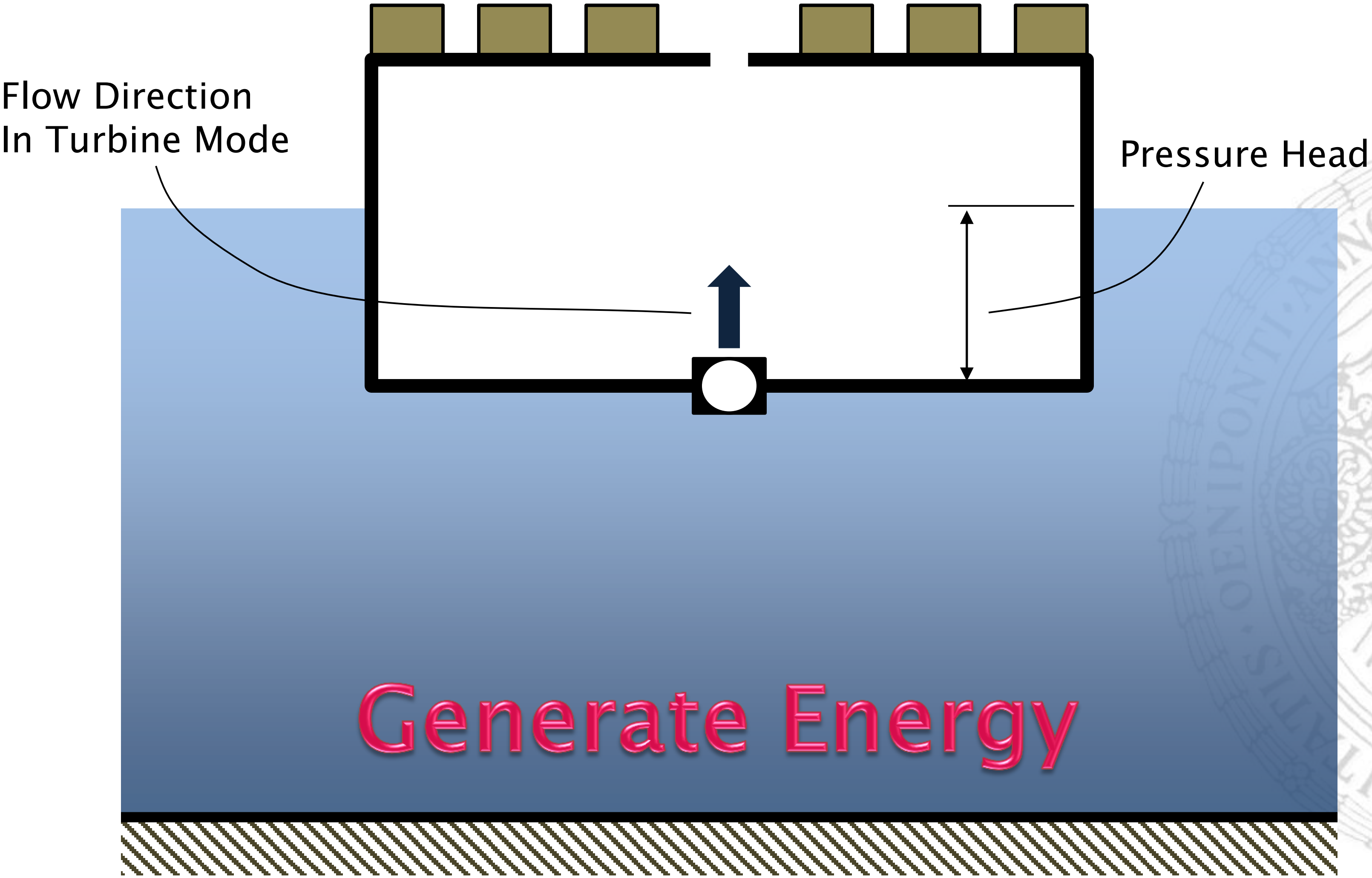
Floating Hydraulic Energy Storage



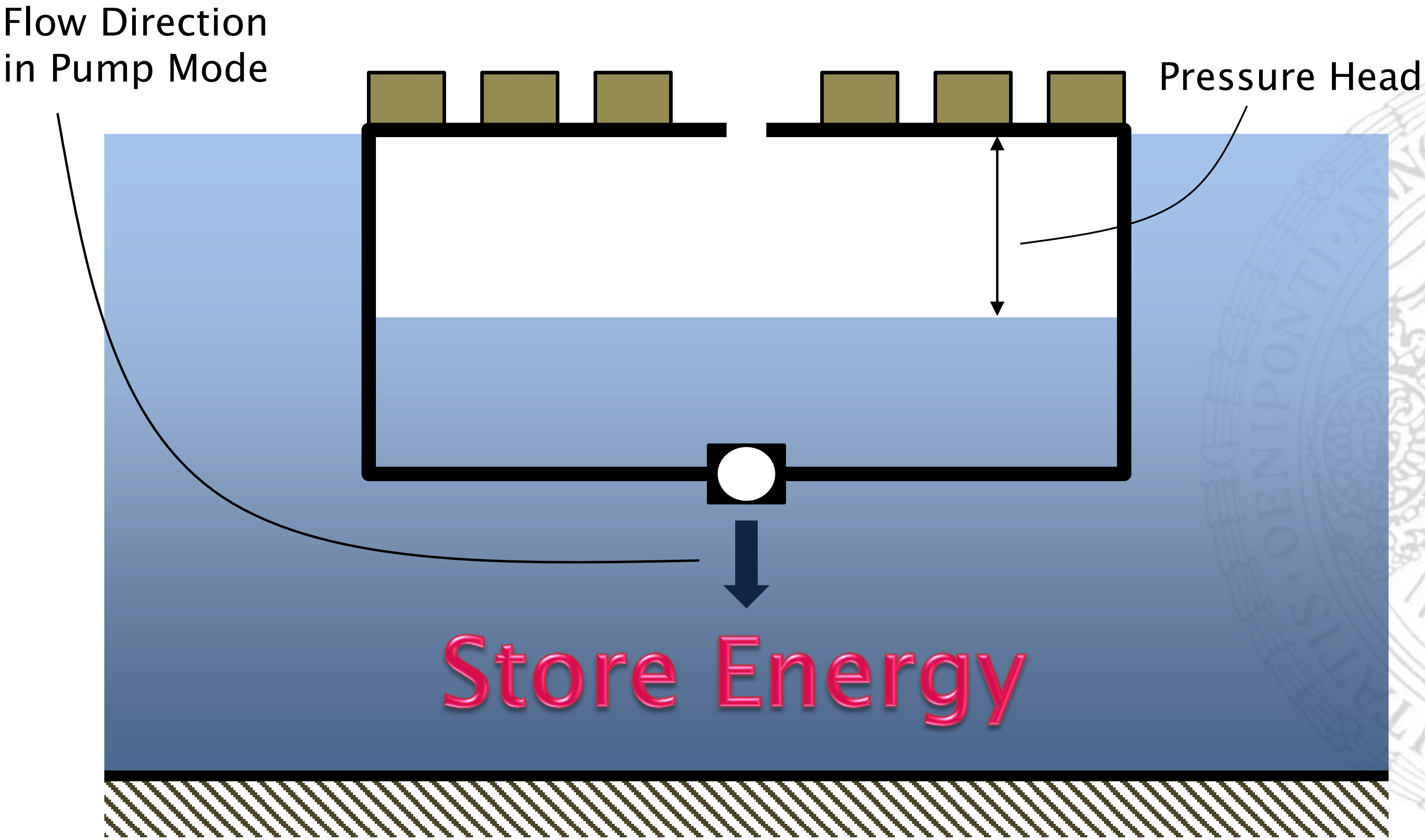
Concept of “Hydraulic Energy Storage”



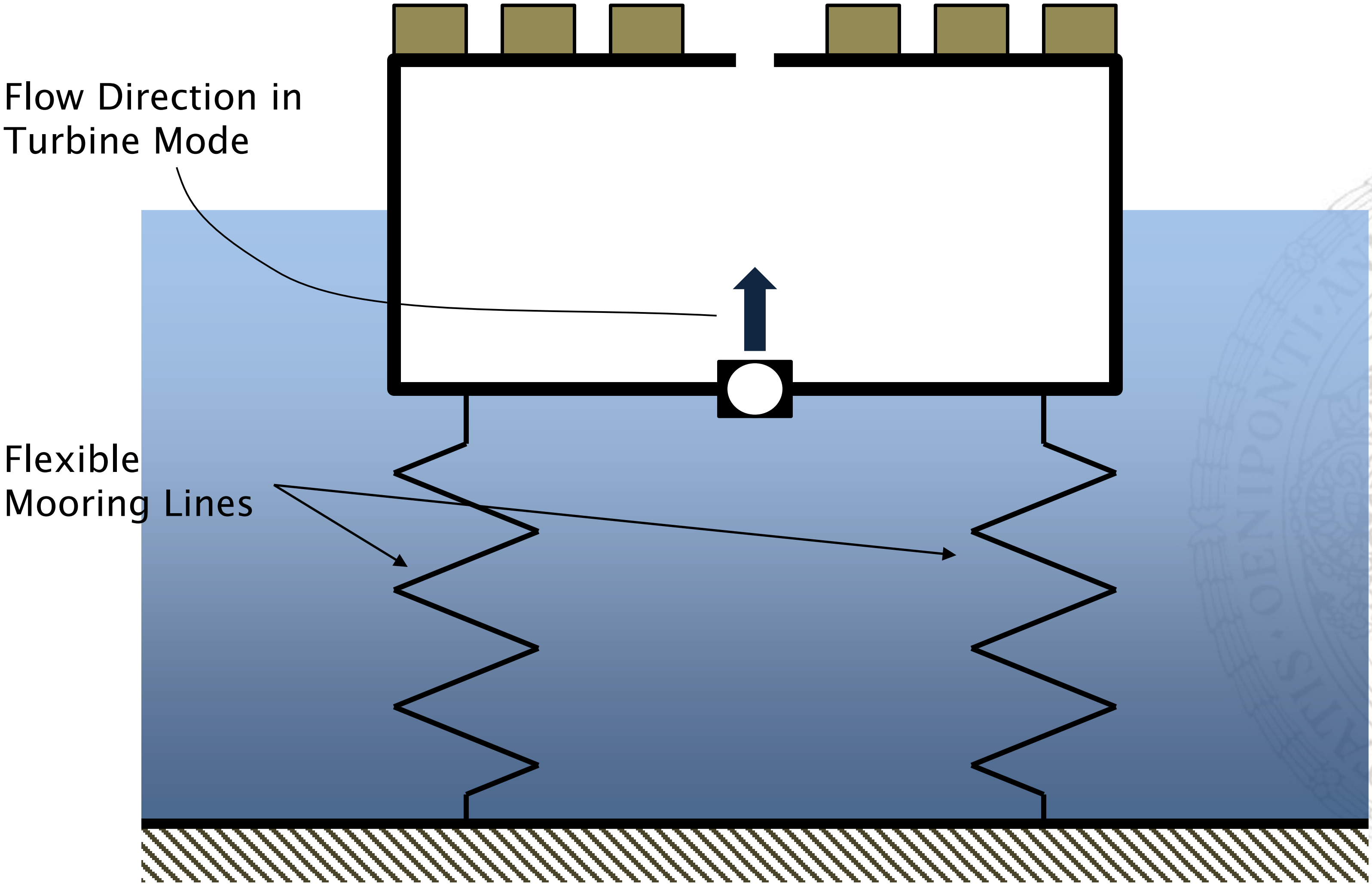
Concept of "Hydraulic Energy Storage"



Concept of “Hydraulic Energy Storage”



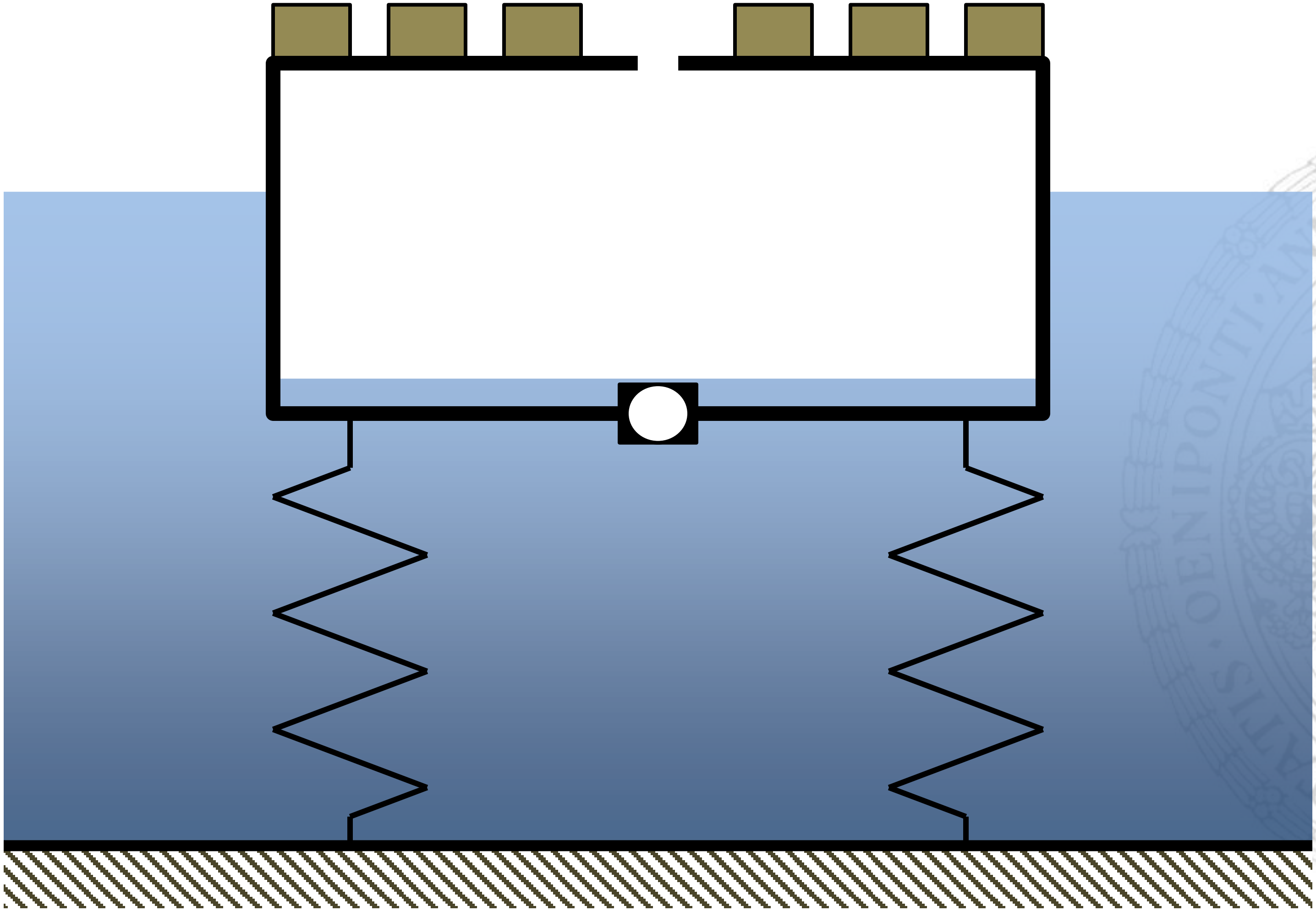
Variation 1: Flexible Mooring Lines



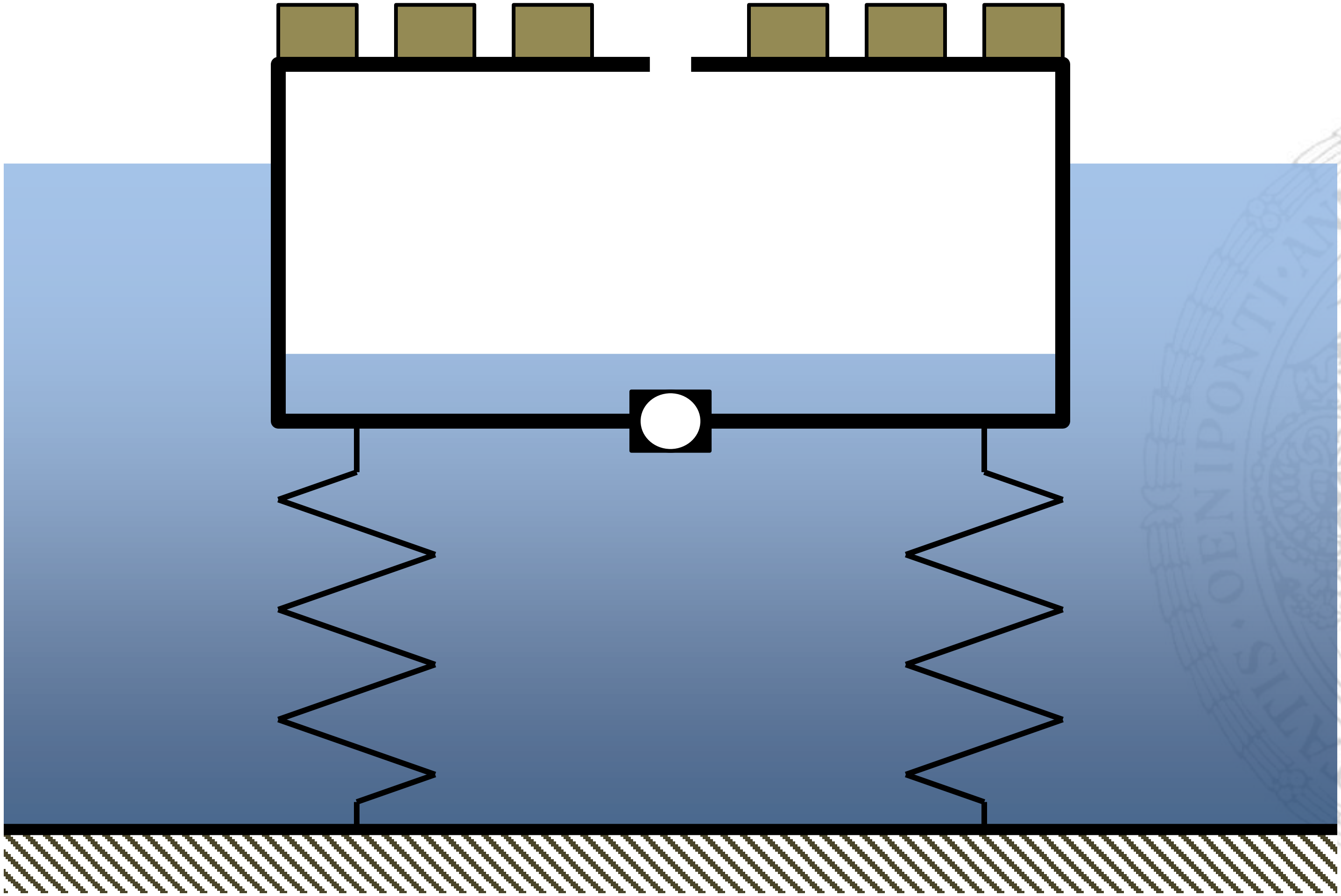
Flow Direction in Turbine Mode

Flexible Mooring Lines

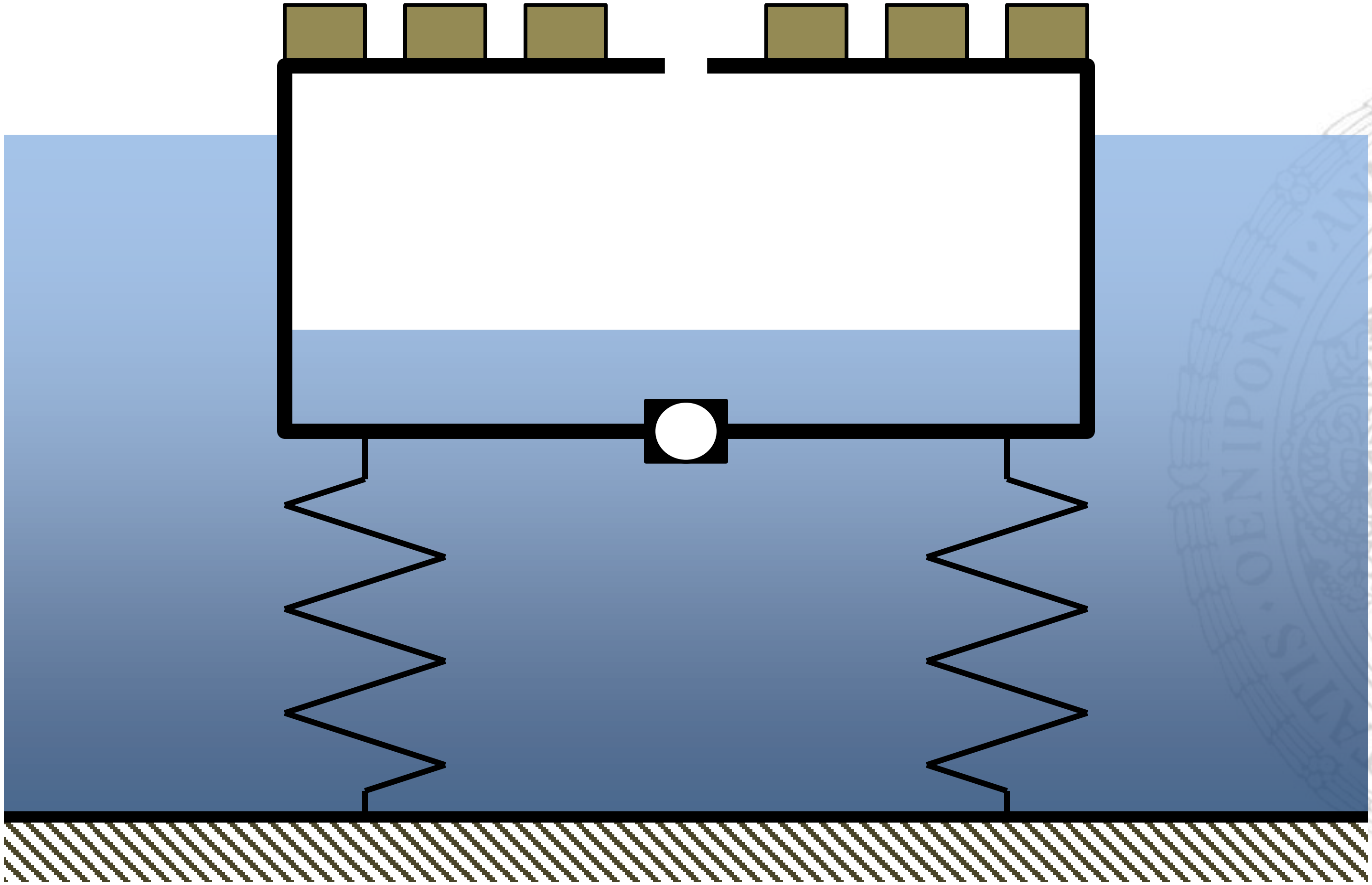
Variation 1: Flexible Mooring Lines



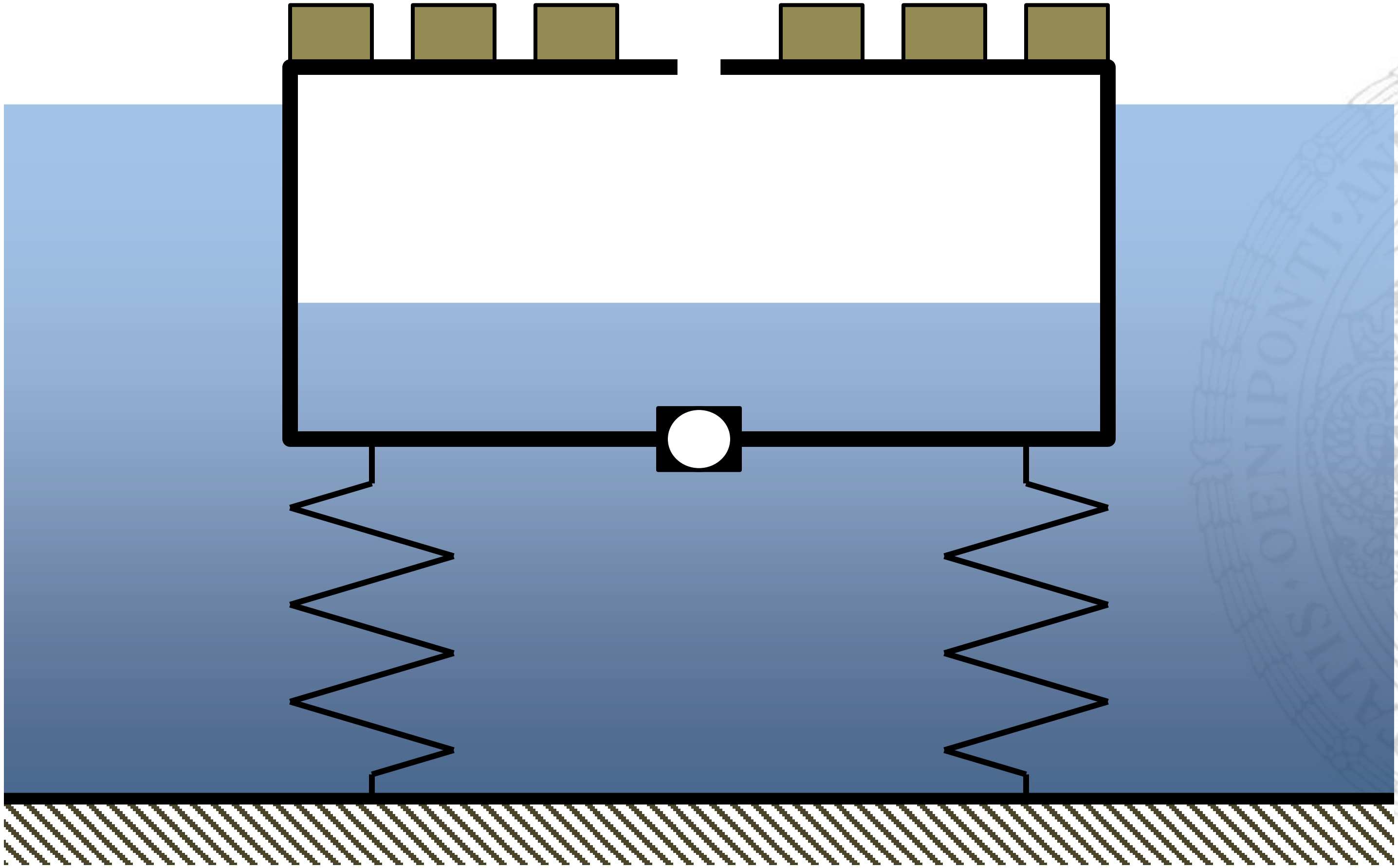
Variation 1: Flexible Mooring Lines



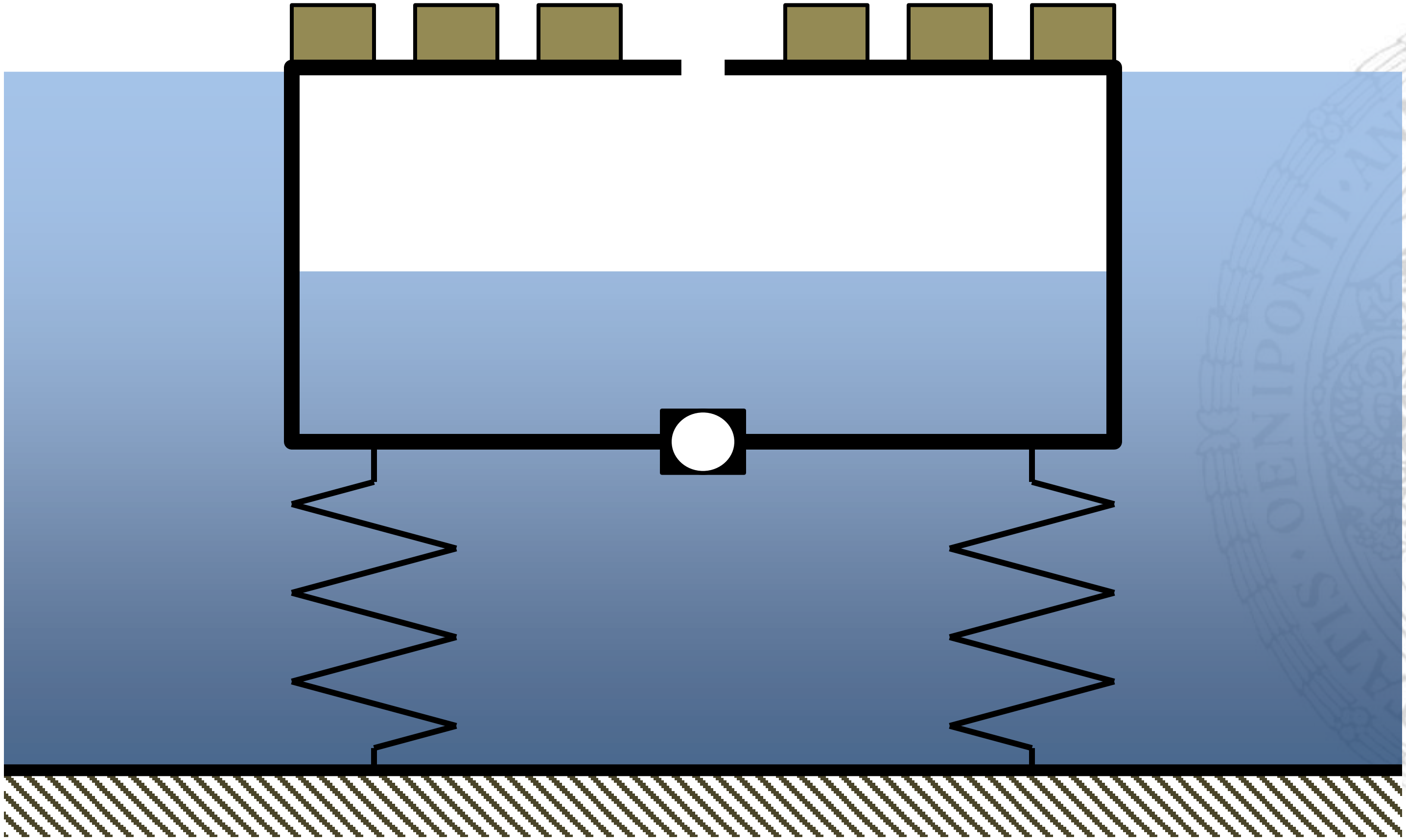
Variation 1: Flexible Mooring Lines



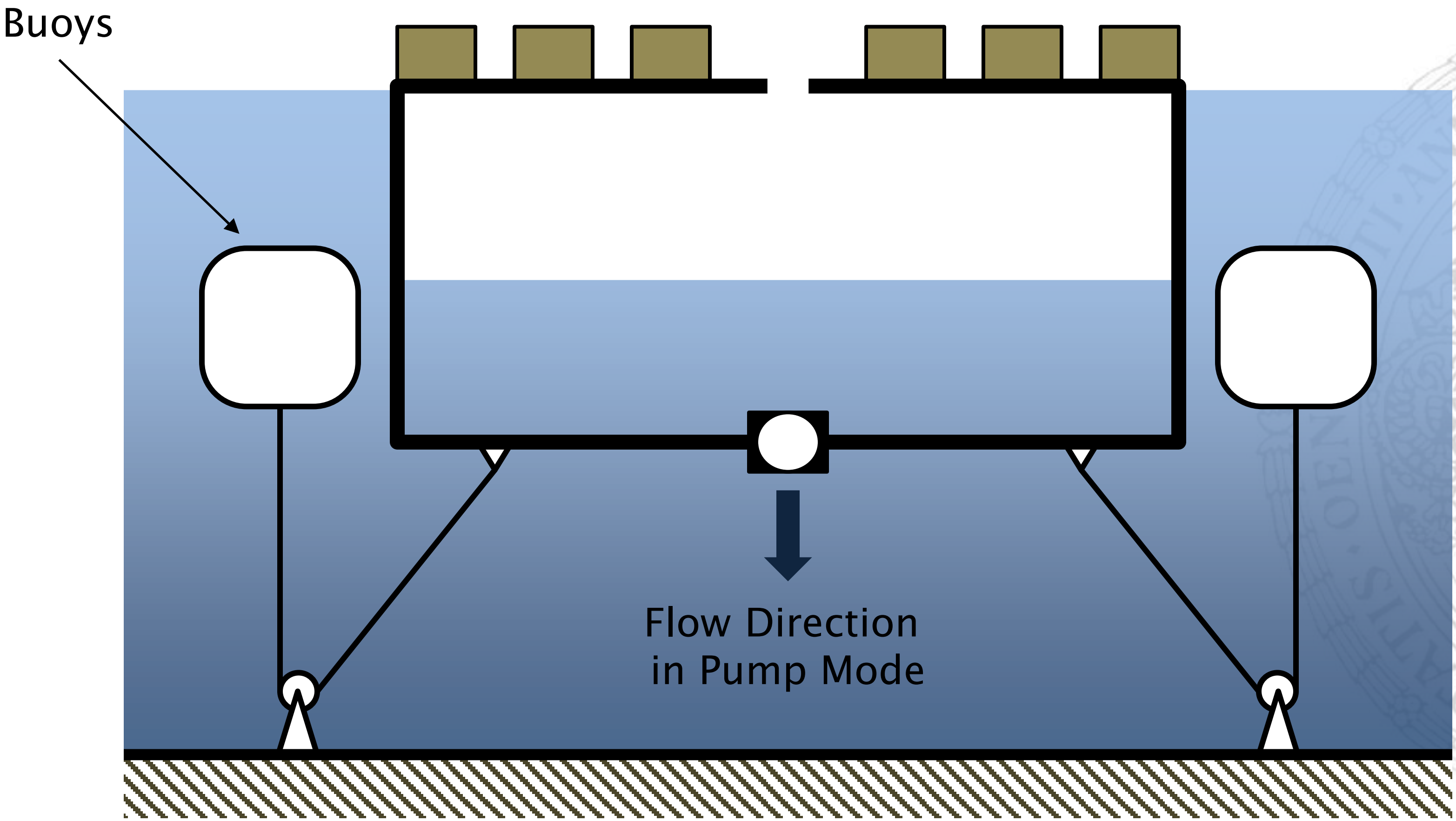
Variation 1: Flexible Mooring Lines



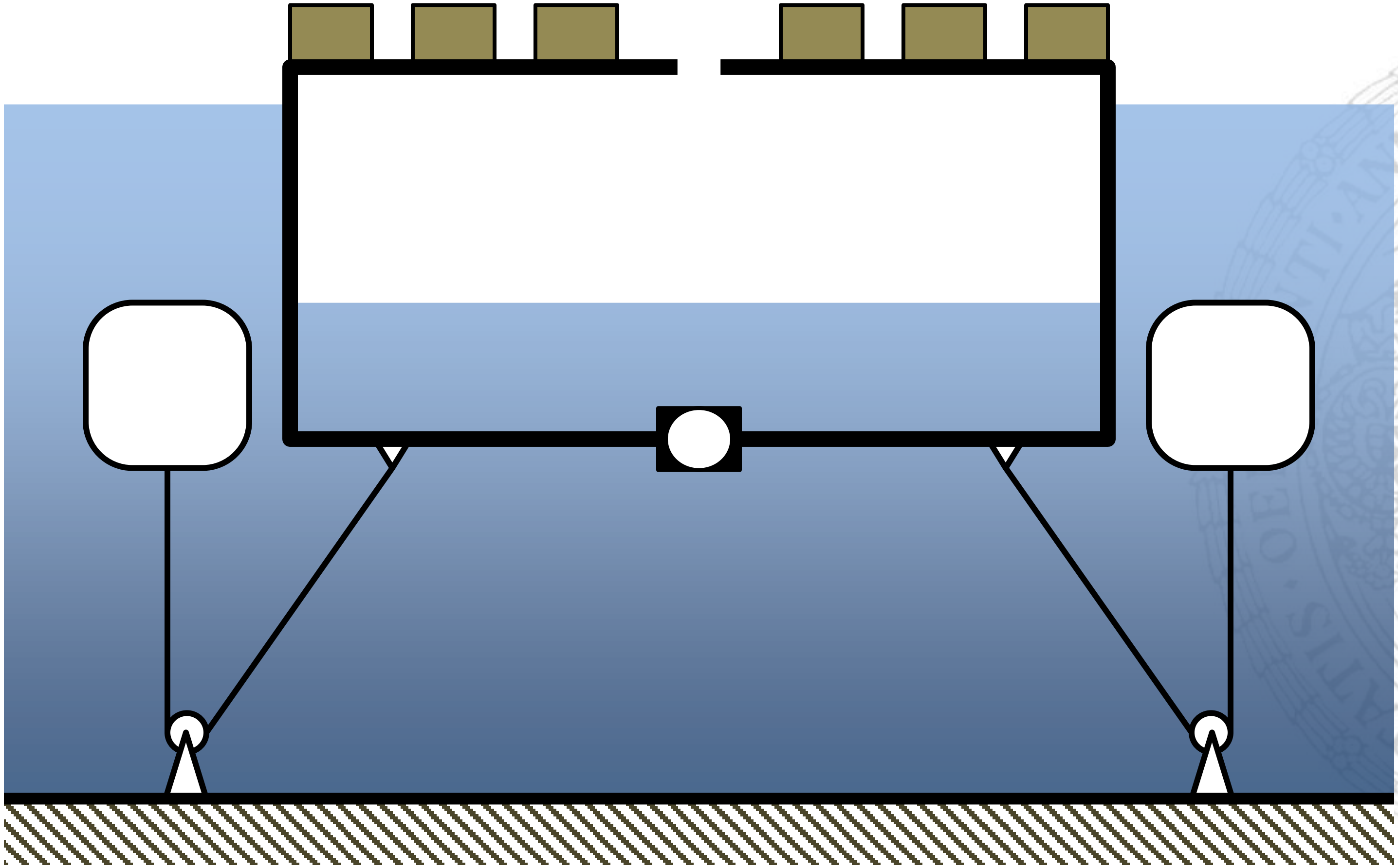
Variation 1: Flexible Mooring Lines



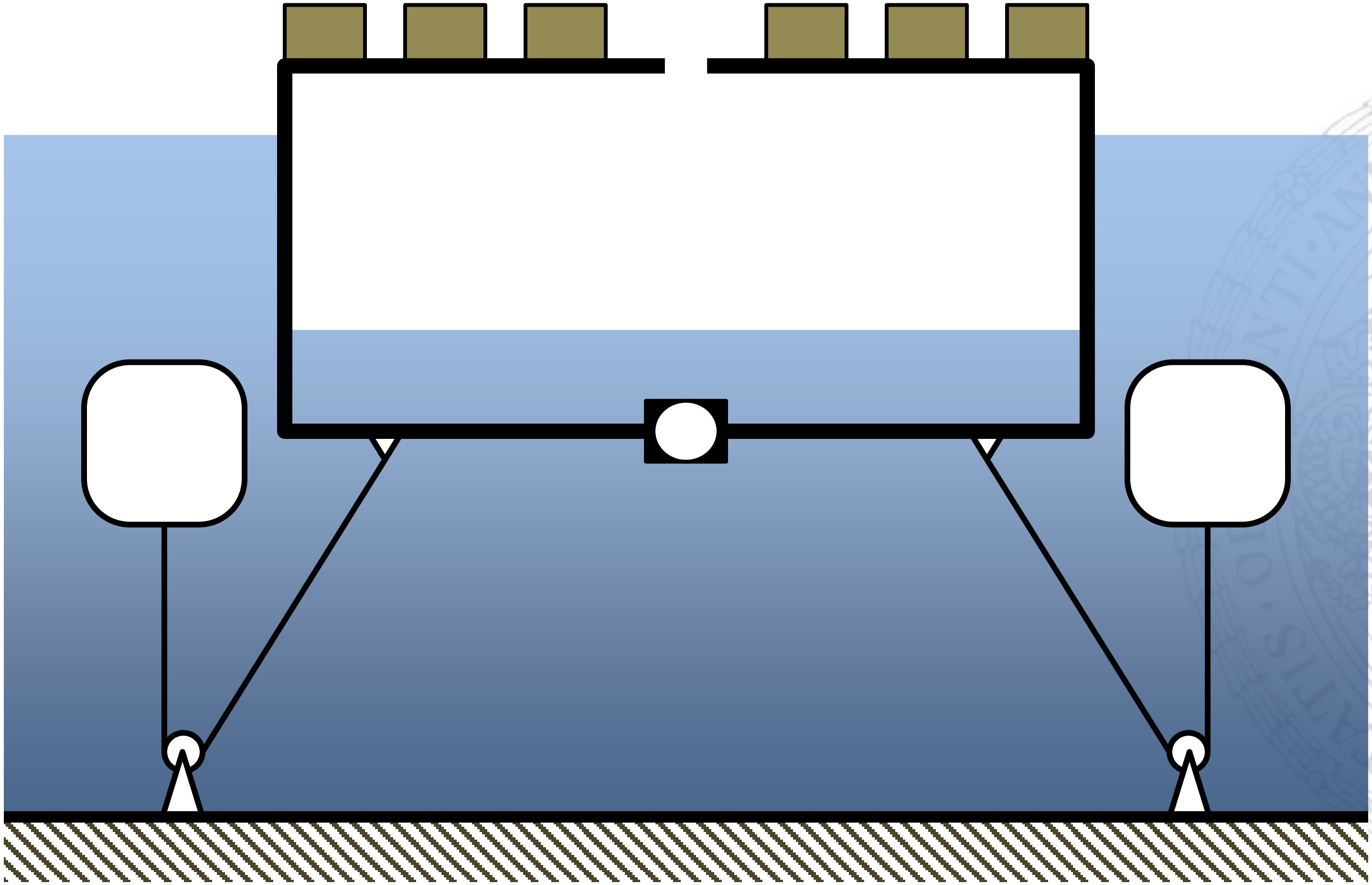
Variation 2: Mooring Lines attached to Buoys



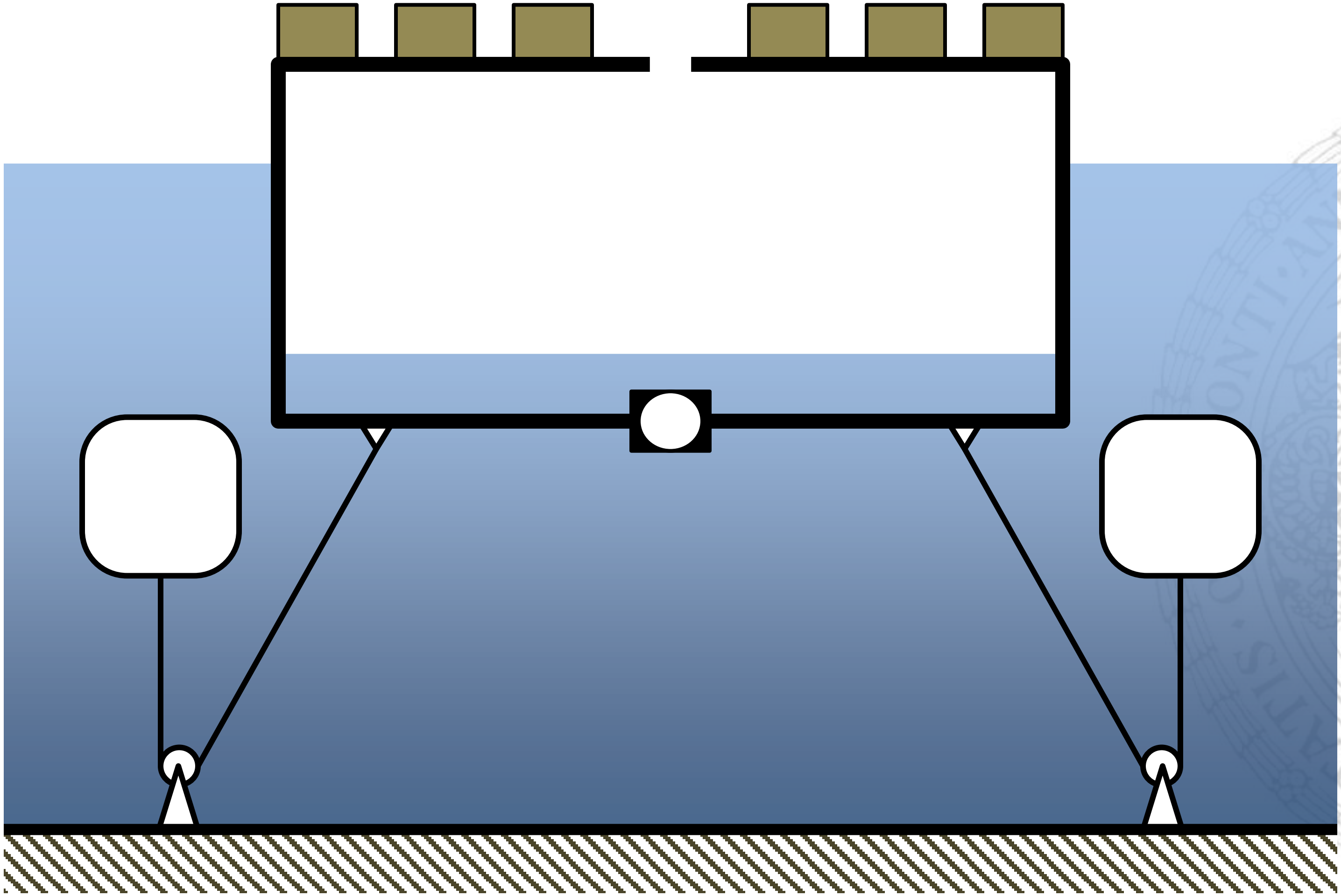
Variation 2: Mooring Lines attached to Buoys



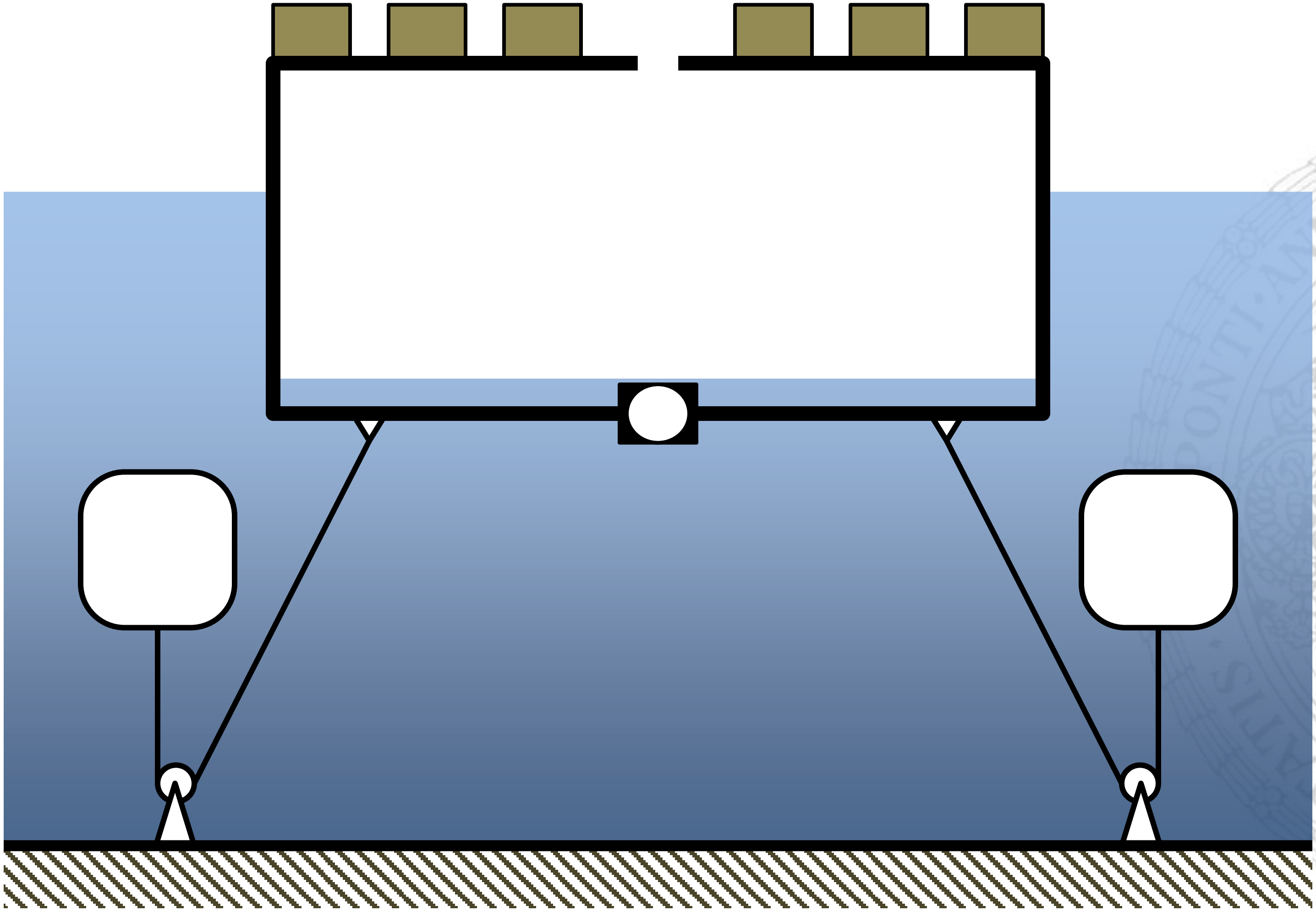
Variation 2: Mooring Lines attached to Buoys



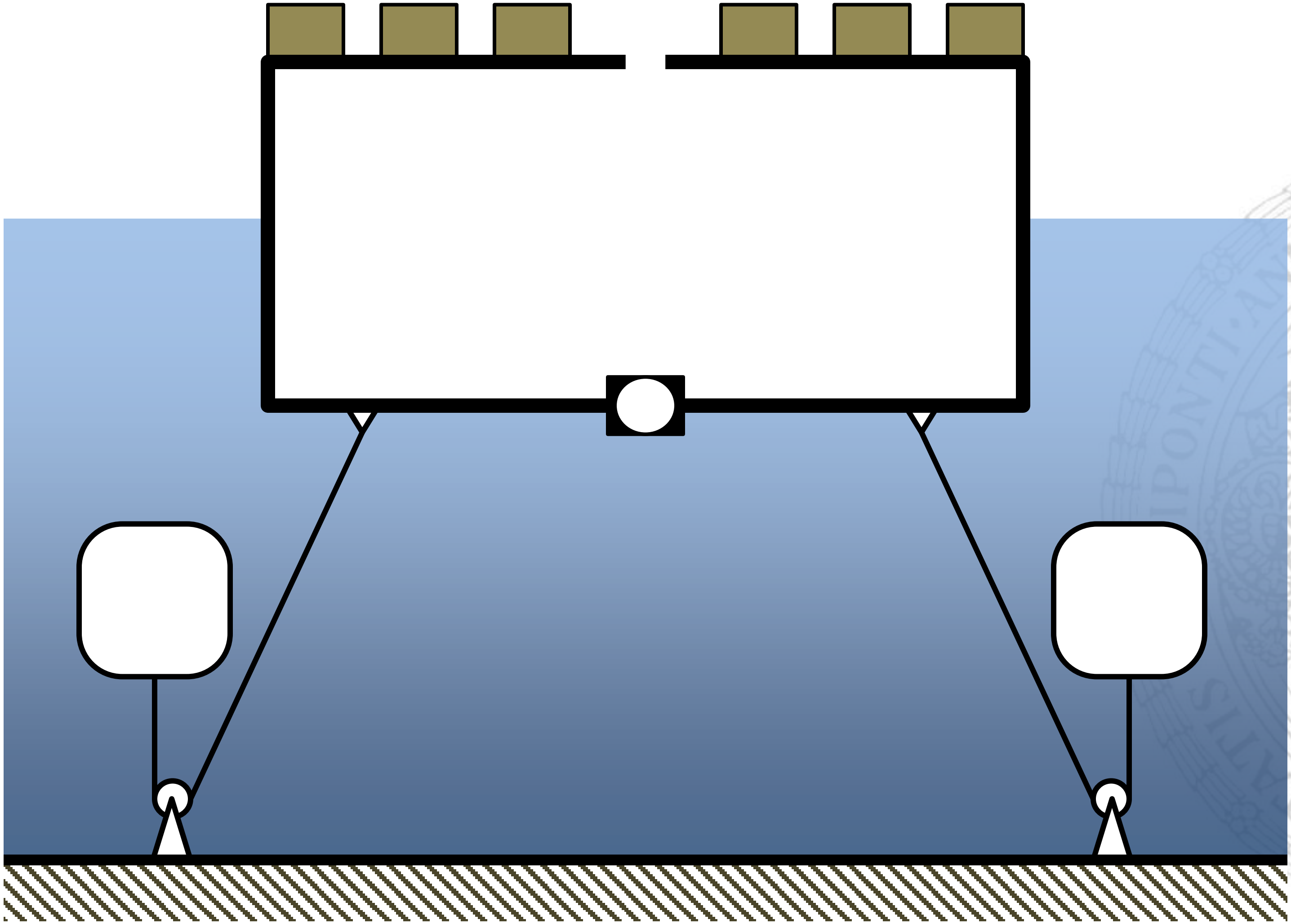
Variation 2: Mooring Lines attached to Buoys



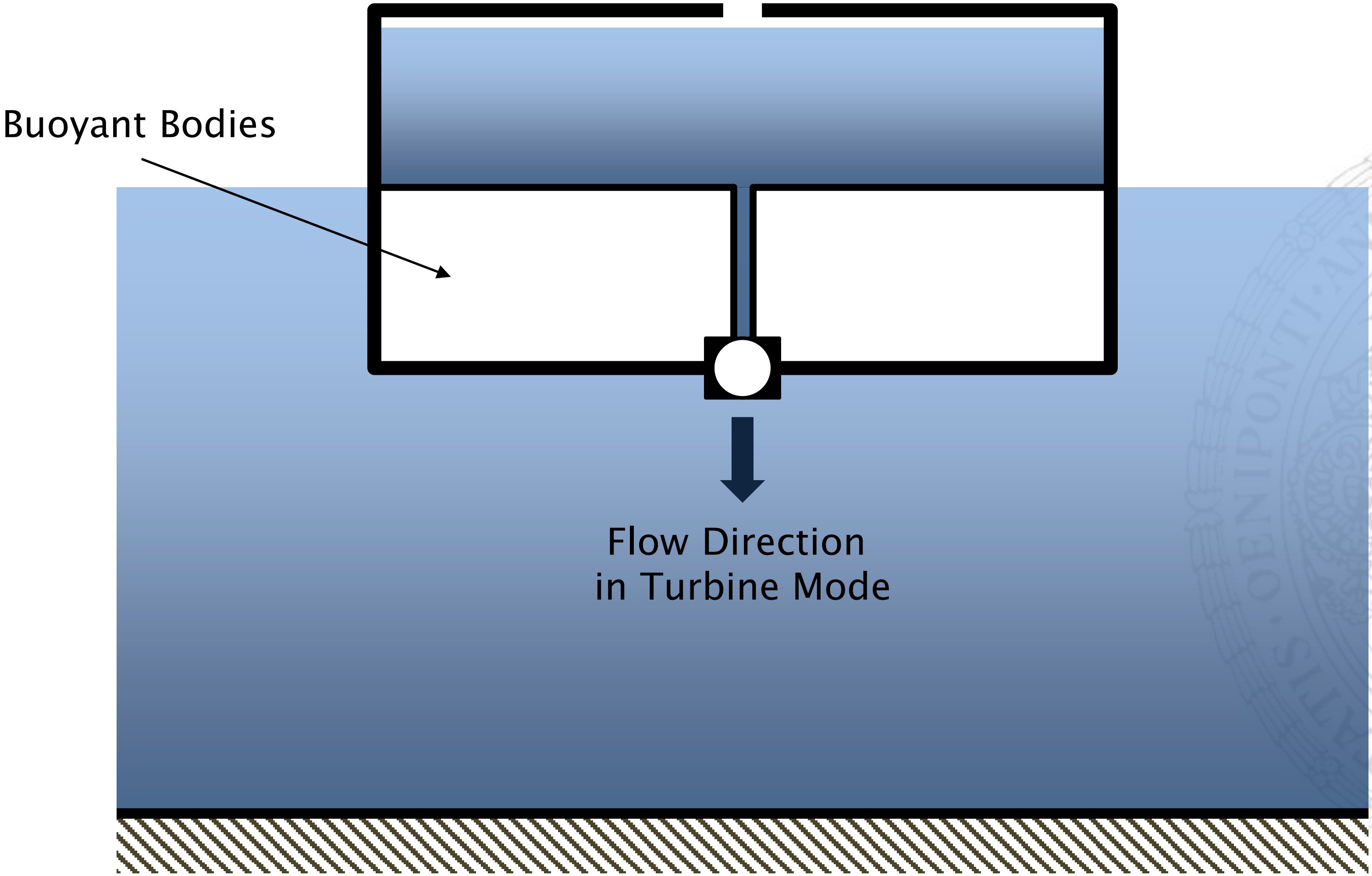
Variation 2: Mooring Lines attached to Buoys



Variation 2: Mooring Lines attached to Buoys



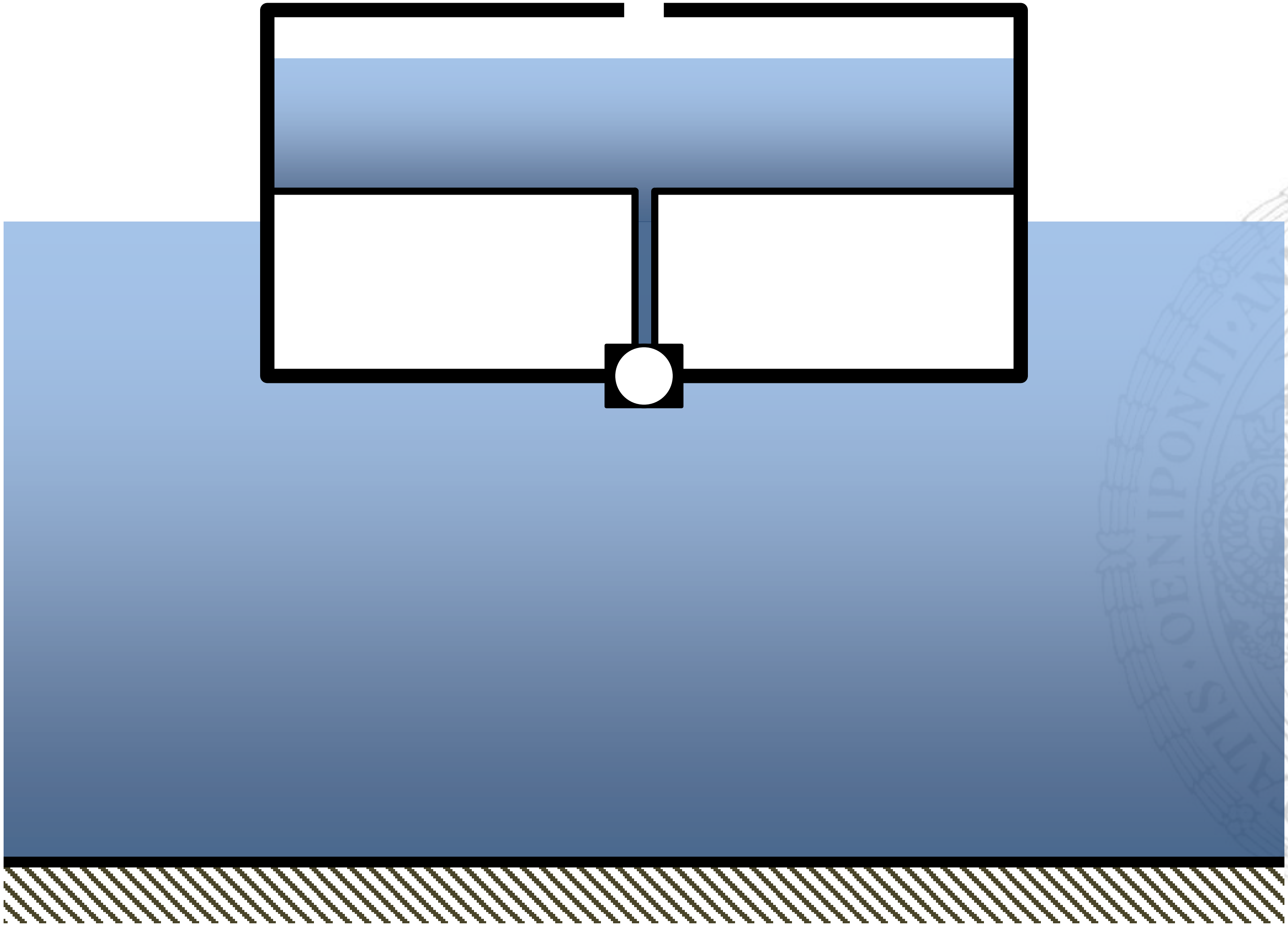
Variation 3: Reversed Energy Conversion



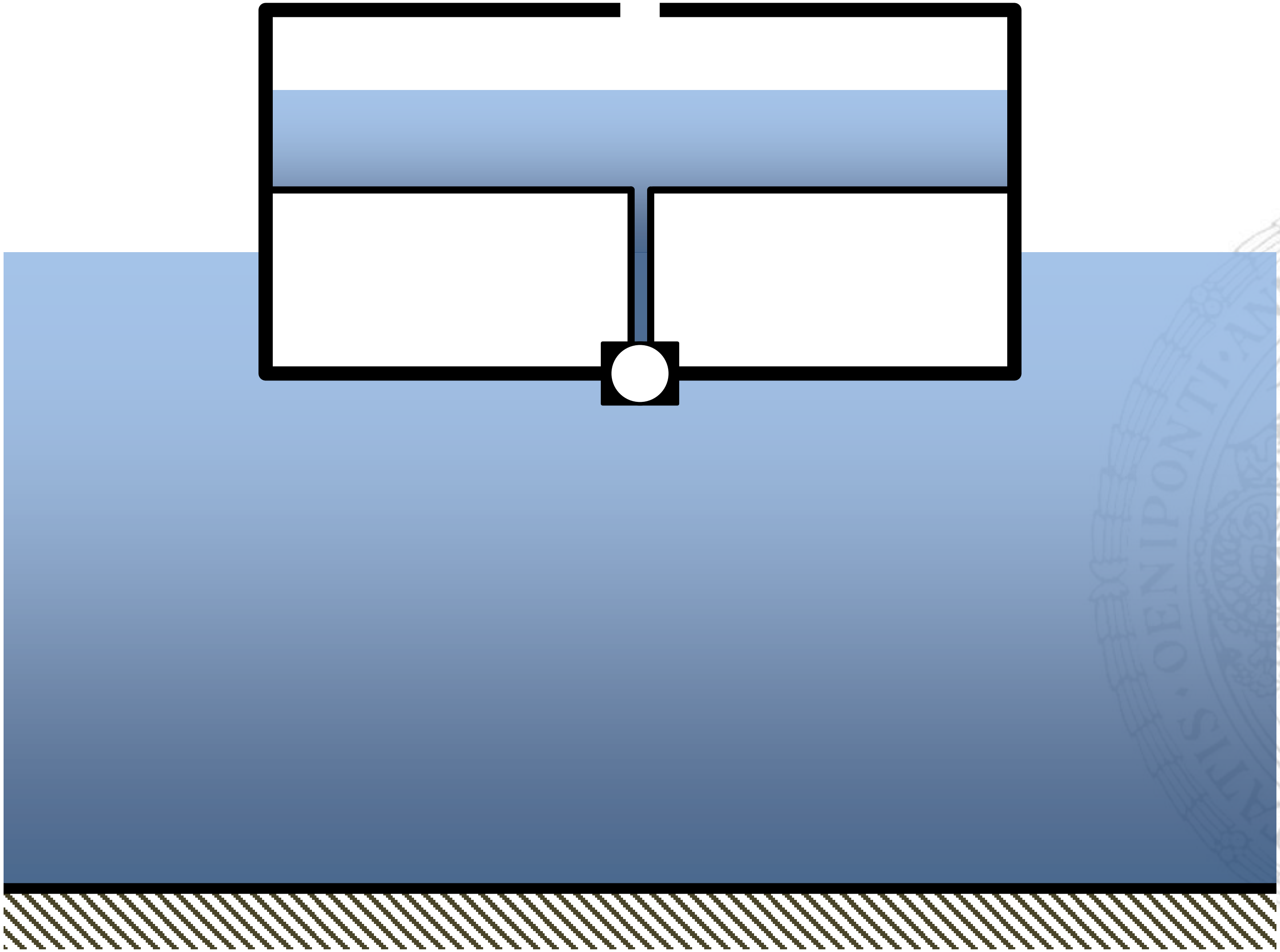
Buoyant Bodies

Flow Direction
in Turbine Mode

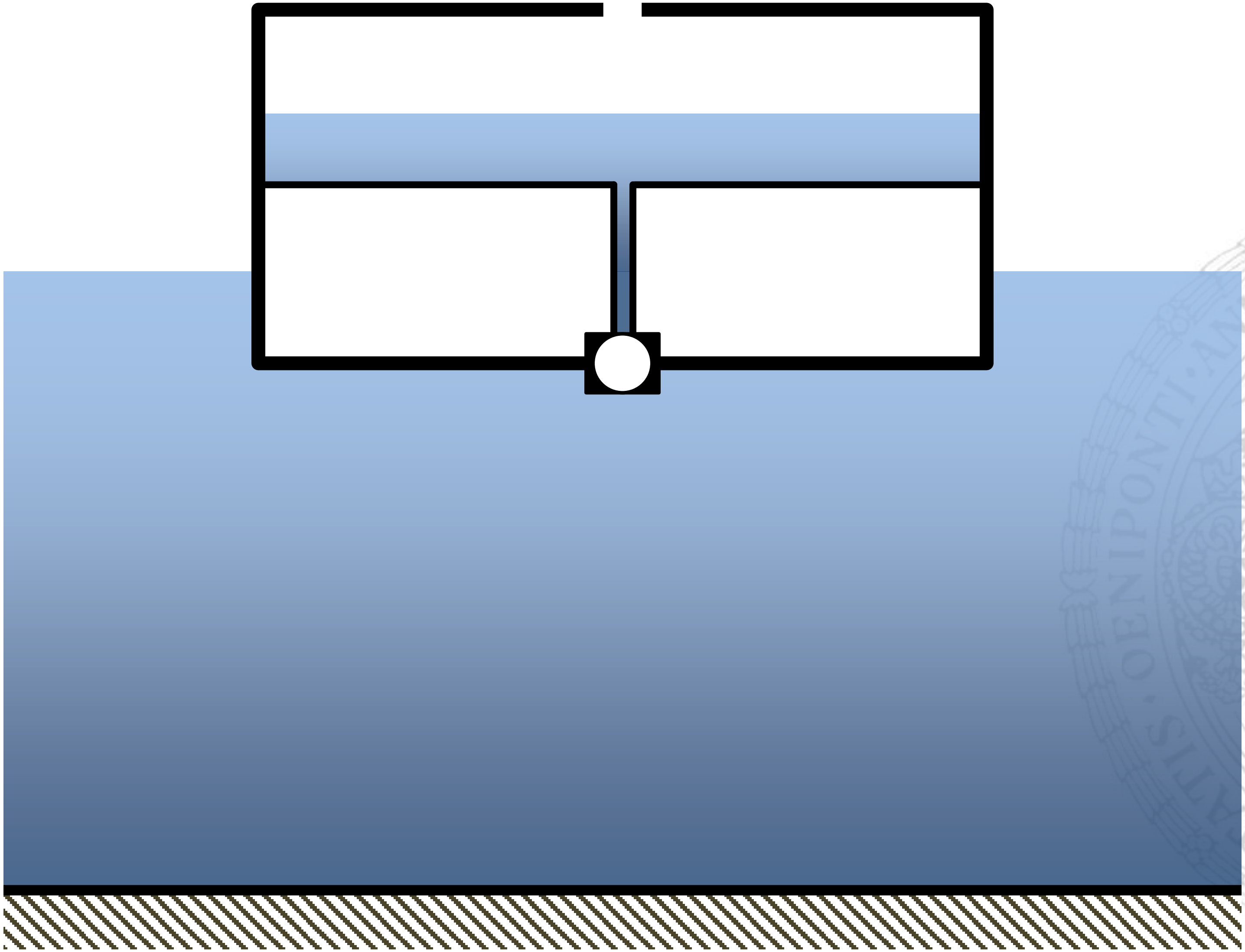
Variation 3: Reversed Energy Conversion



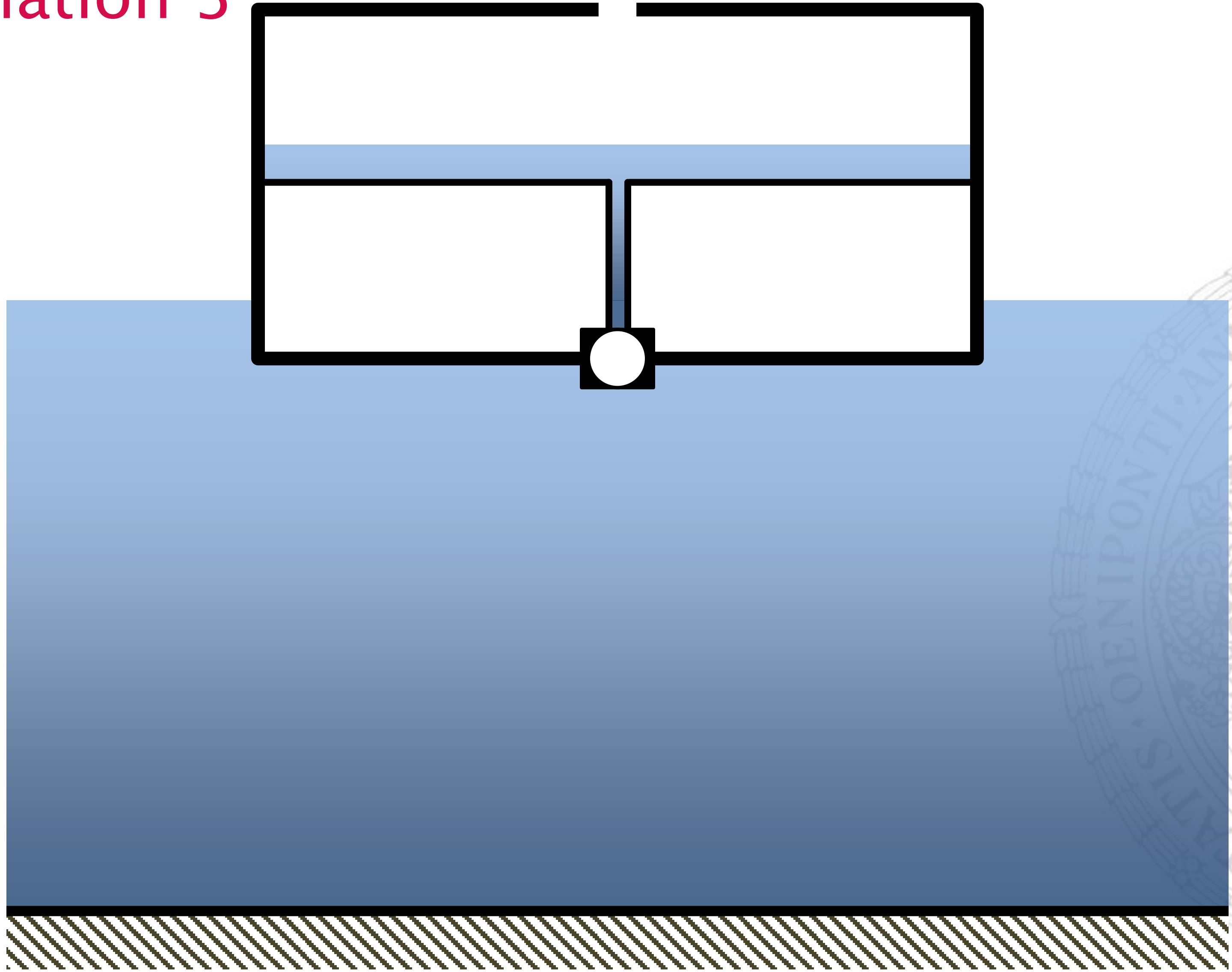
Variation 3: Reversed Energy Conversion



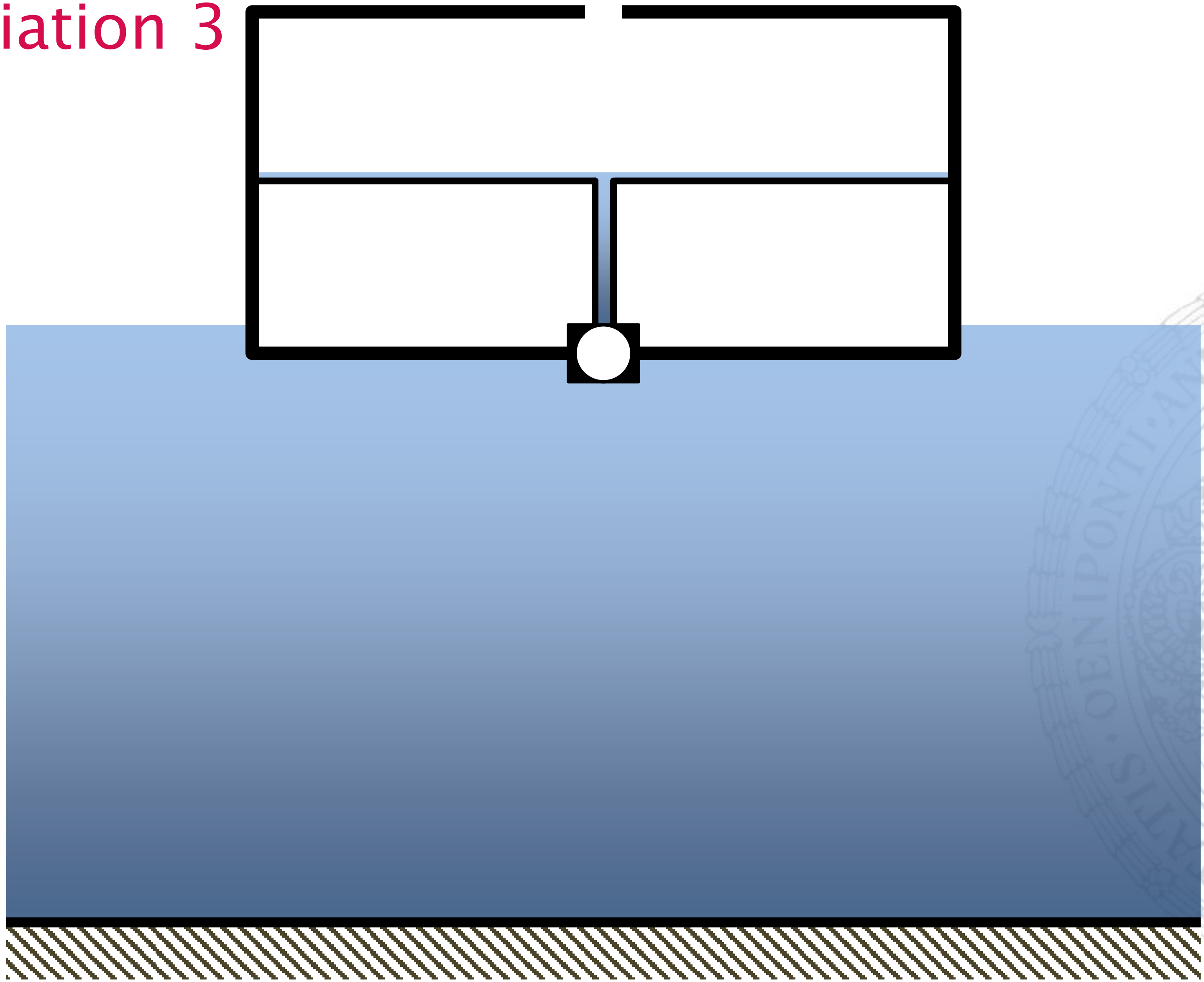
Variation 3



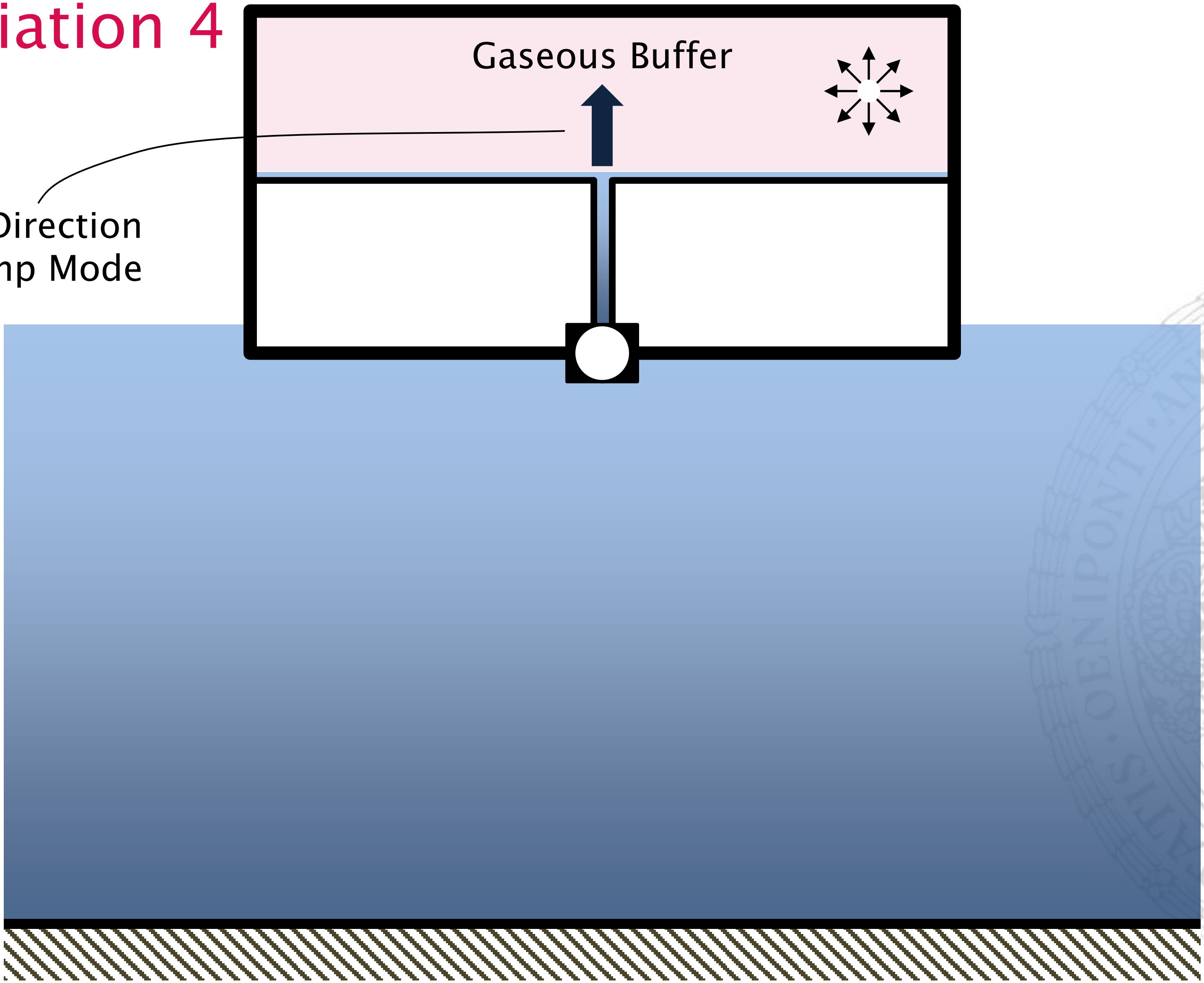
Variation 3



Variation 3



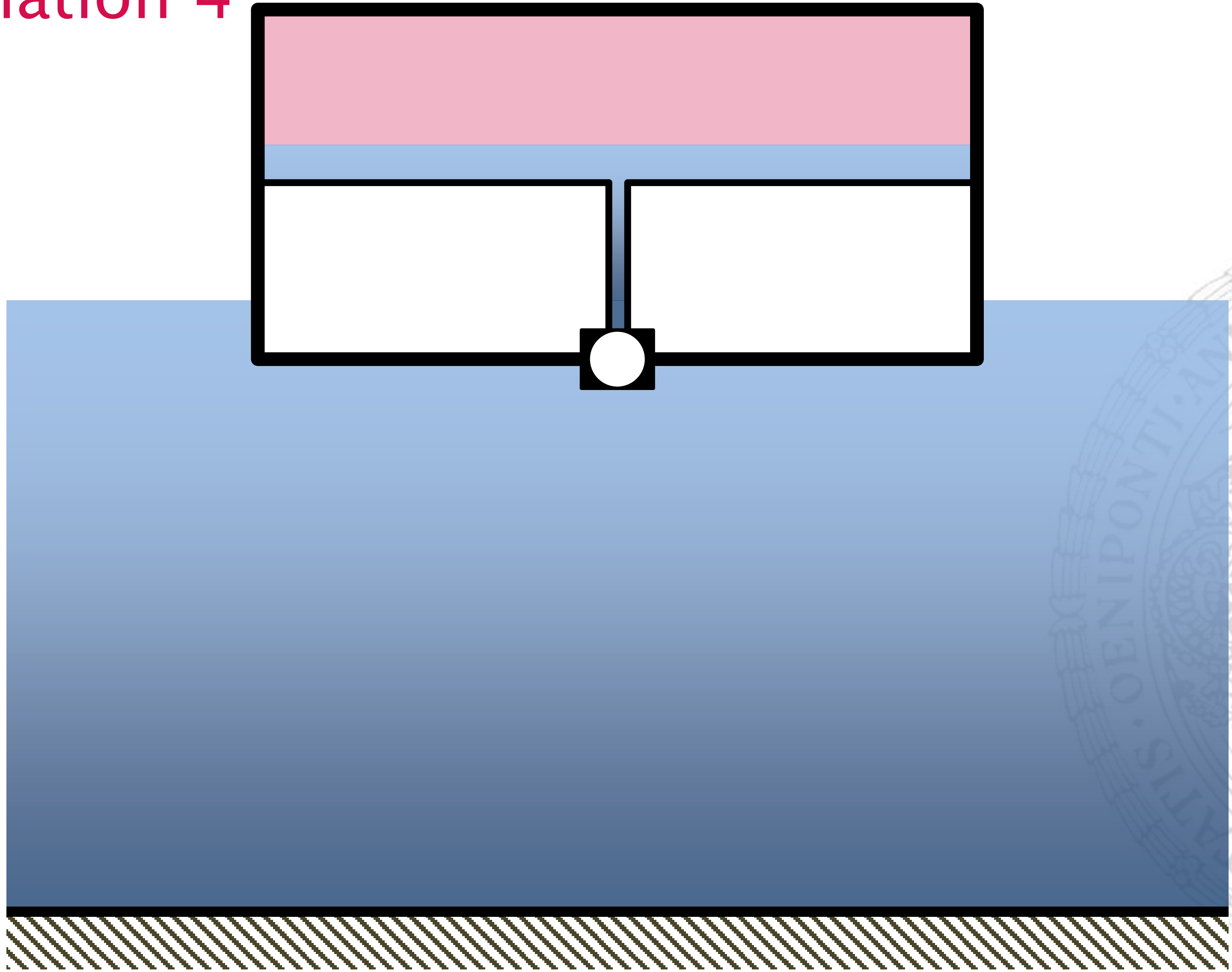
Variation 4



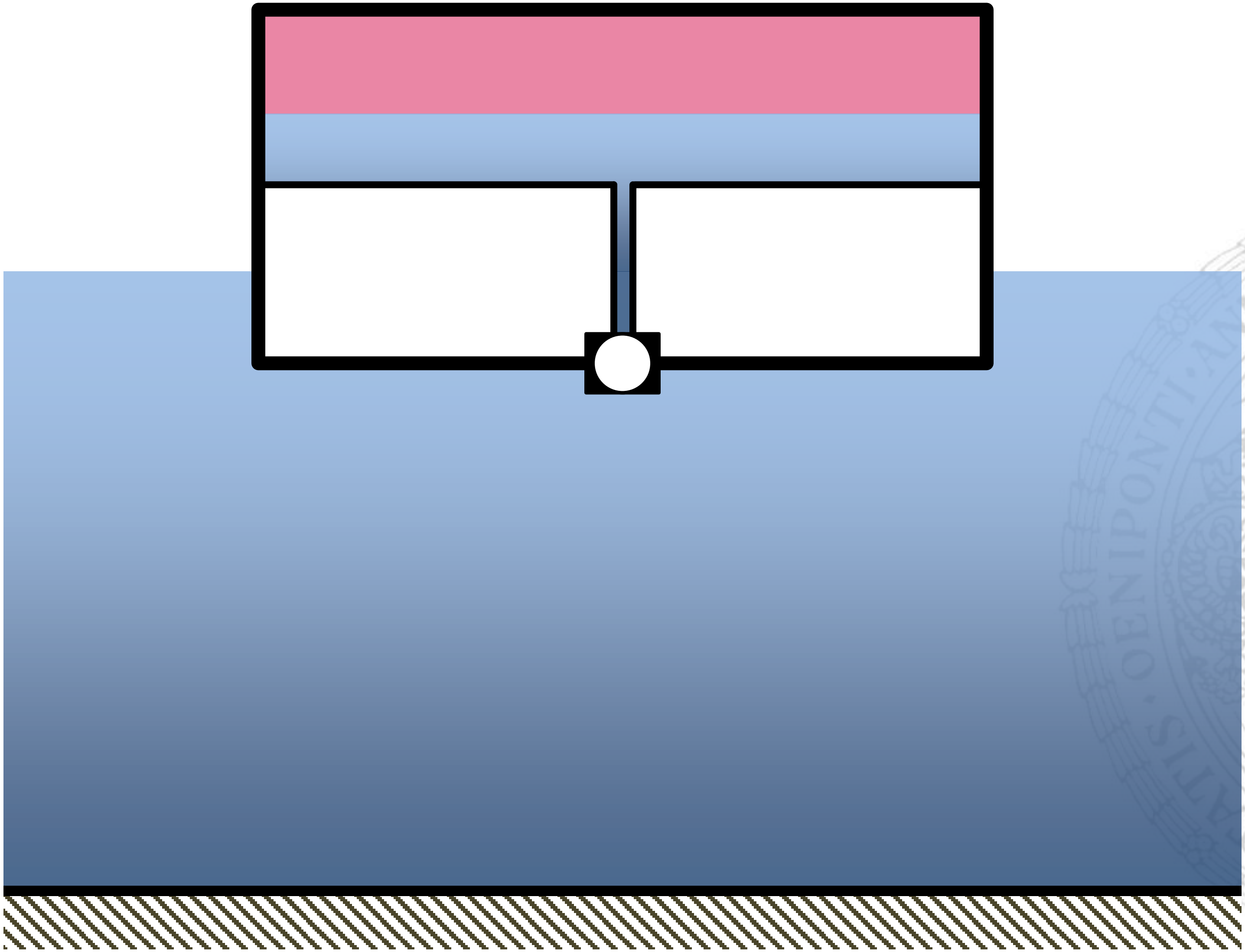
Gaseous Buffer

Flow Direction
In Pump Mode

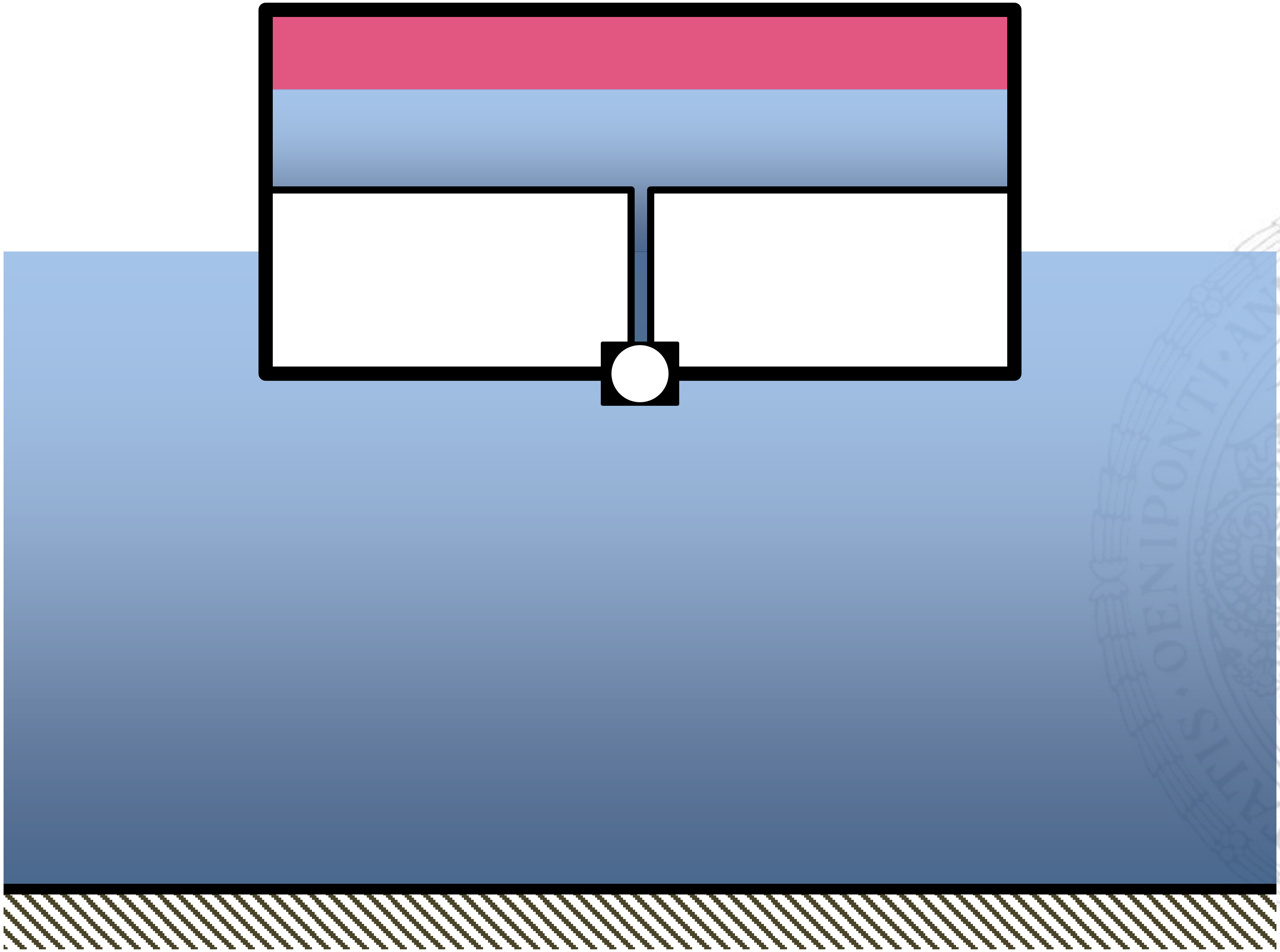
Variation 4



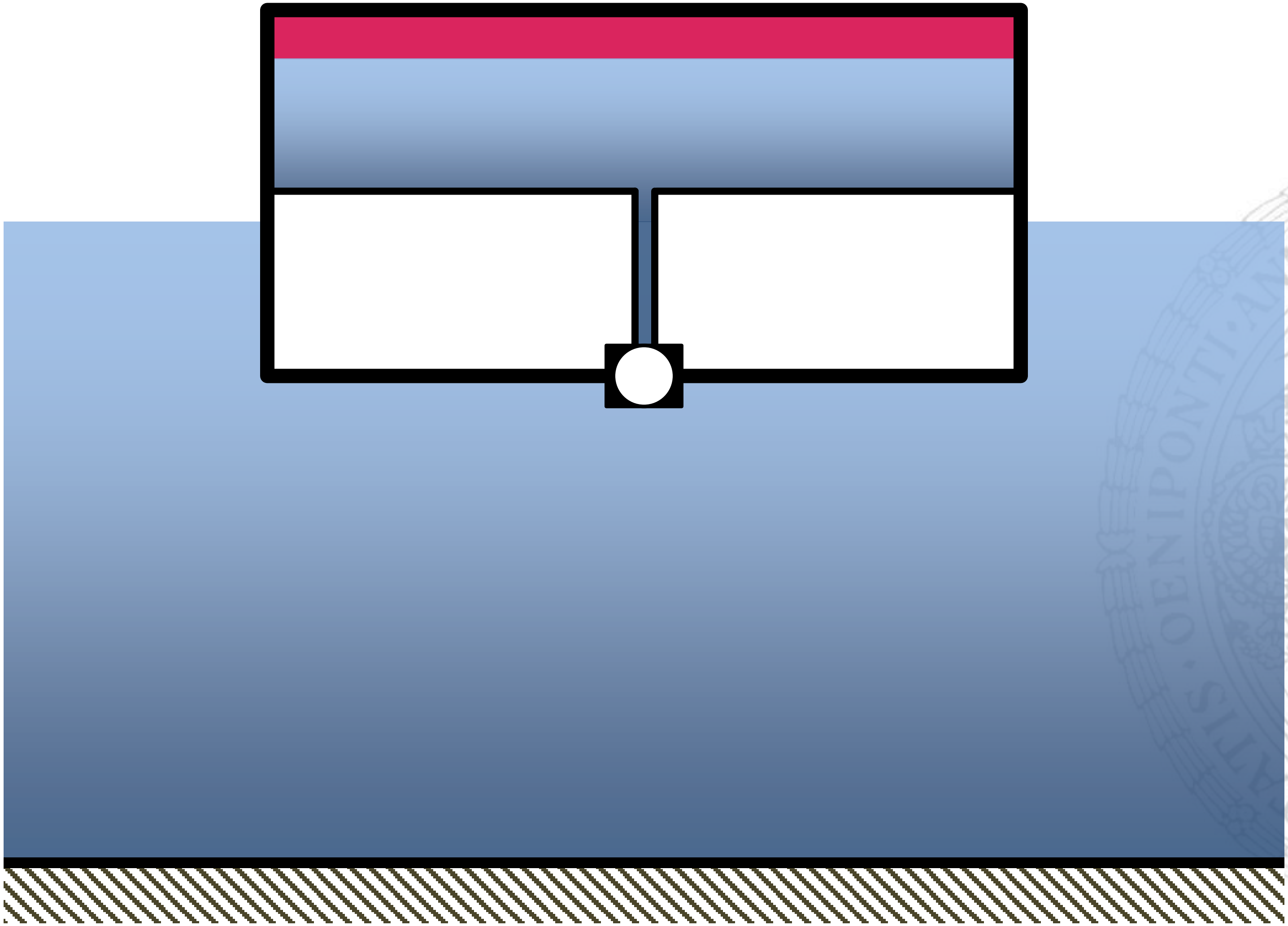
Variation 4



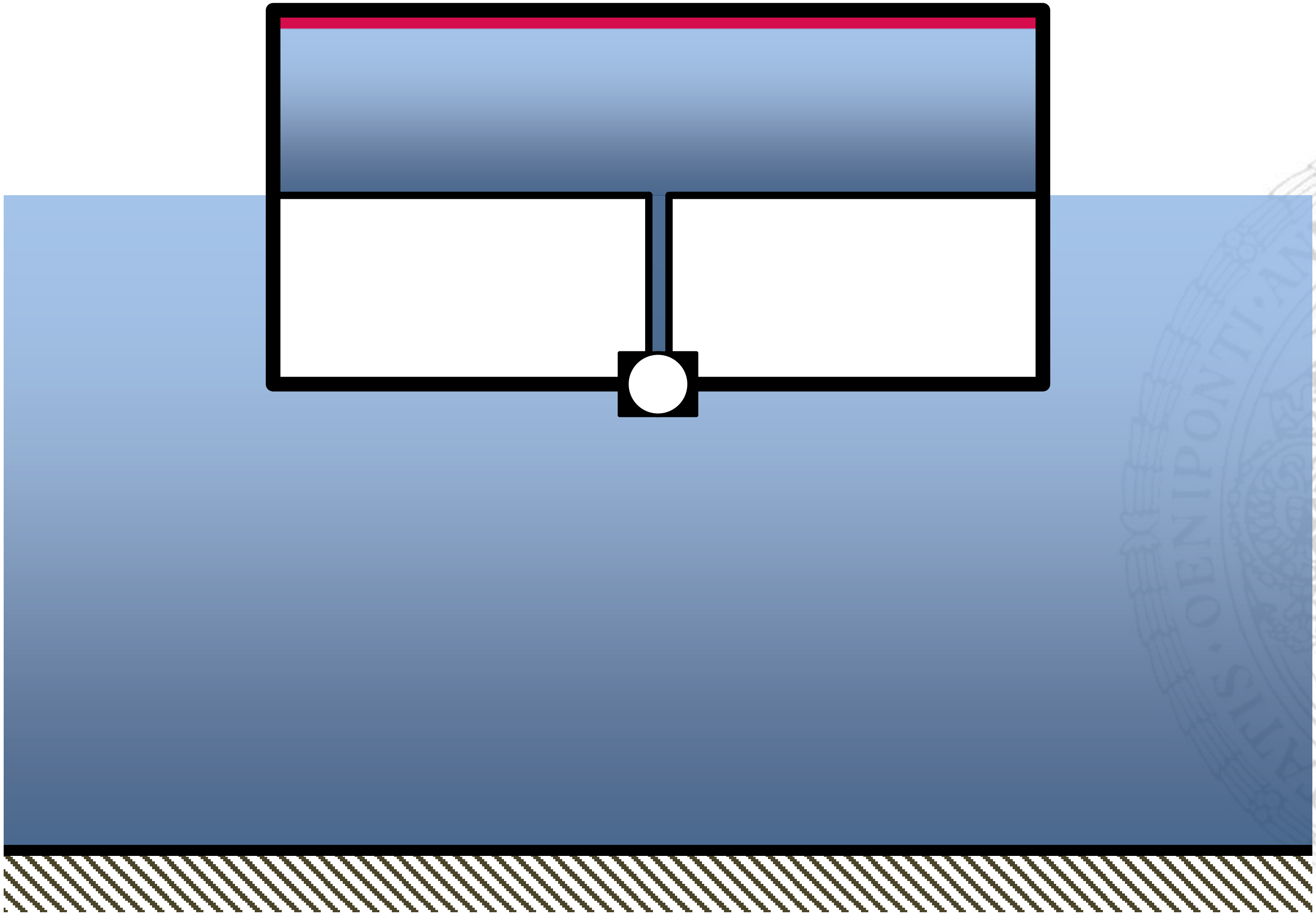
Variation 4



Variation 4



Variation 4



Unique Traits

Unique Traits of floating hydraulic energy storage plants based on the *Buoyant Energy* principle.

Unique Traits

- Highly efficiency
  - Due to low hydraulic losses; constant pressure head possible
- Unlimited number of cycles
- Response time is within the range of a few seconds
- Self-discharge rate is irrelevantly small
- Rapid load changes are possible
  - Hydraulic short circuit
- Robust proven technology in a new environment

Unique Traits

- Decentralized energy storage at the site of production
  - Minimal expansion of the transmission network
- Diverse combination possibilities
  - Demand for offshore energy, aquaculture and transport infrastructure (*“offshore terminals”*, maritime service platforms) is growing
  - Hydraulic energy storage plants can be combined with just about any other platform design

Unique Traits

- Combination of floating offshore infrastructure with energy storage:
  - Platforms with functional buildings ("Floatels", Aqua-farms, etc.)
  - Service platforms (maintenance, floating container port, etc.)

Source: http://www.floatinghomes.de/

Unique Traits

- Combination of floating offshore infrastructure with energy storage:
  - Platforms with functional buildings ("Floatels", Aqua-farms, etc.)
  - Service platforms (maintenance, floating container port, etc.)

Source: AZ Island, A Floating World Concept

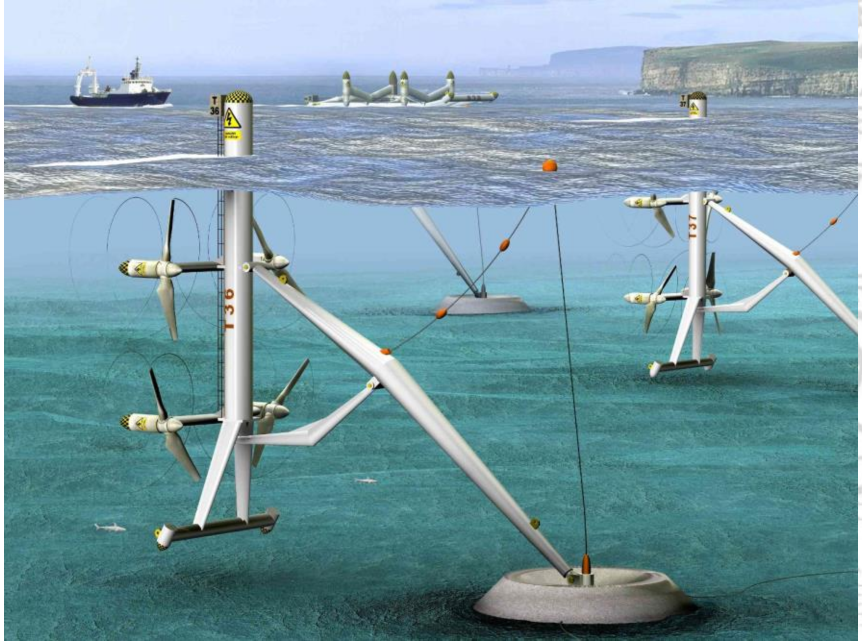
Unique Traits

- Combination of floating offshore infrastructure with energy storage:
  - Platforms with functional buildings ("Floatels", Aqua-farms, etc.)
  - Service platforms (maintenance, floating container port, etc.)

Source: Megafloat

Unique Traits

- Combination of energy production and energy storage
  - ➢ floating solar power plants and ocean current power plants



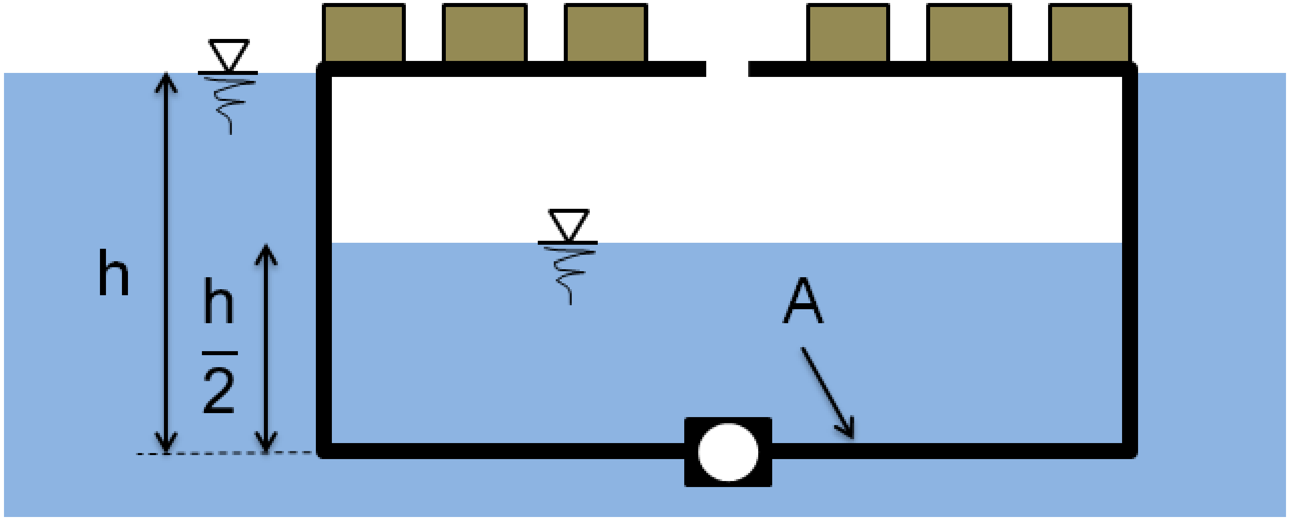
Unique Traits

- Combination of energy production and energy storage
  - ➢ Floating Offshore-Wind Farms – “Floating Wind Turbine”

Source: Siemens-Pressebild

Source: Siemens-Pressebild, „Hywind“

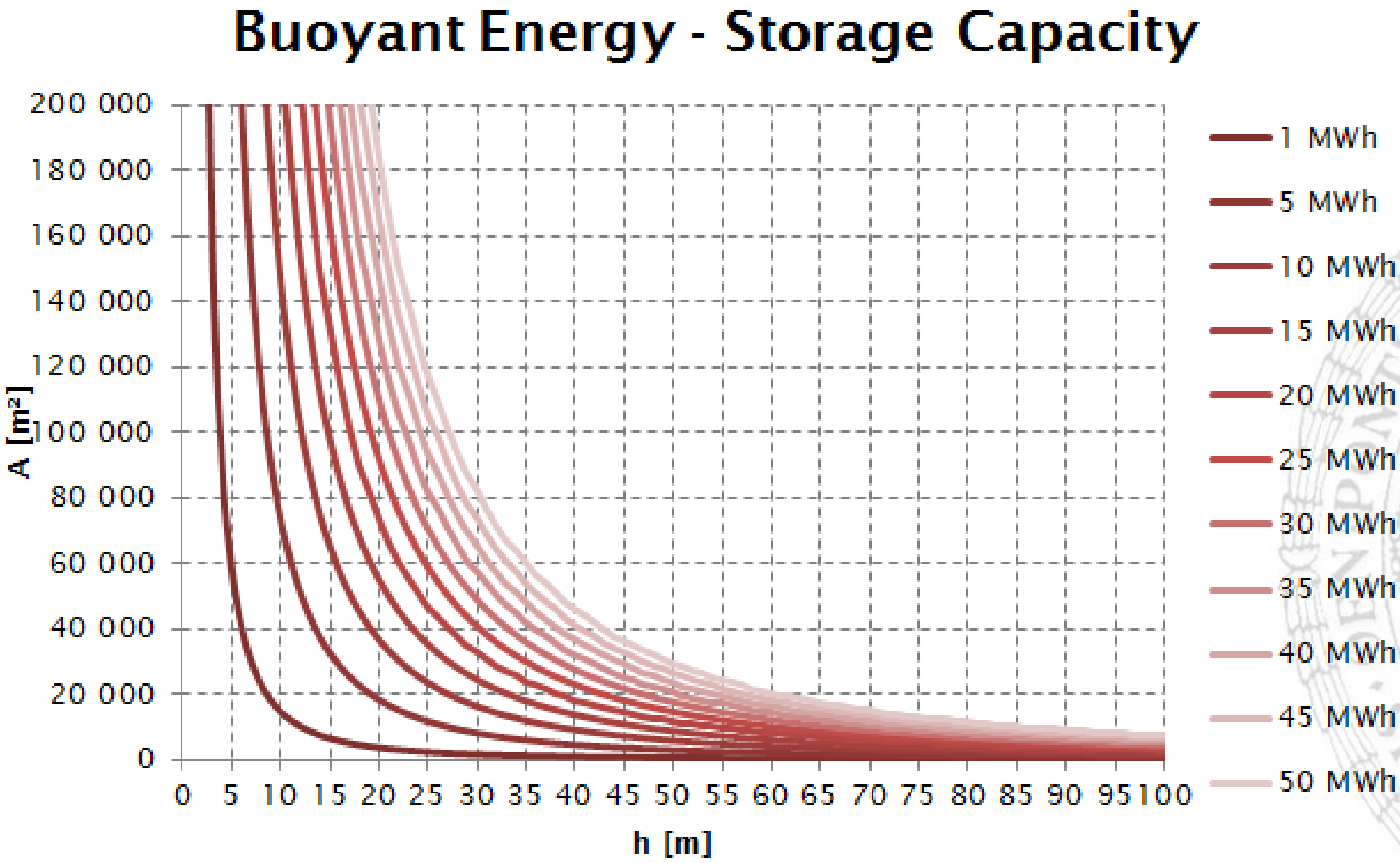
Storage Capacity of an Ideal System



Storage Capacity: $E = m \cdot g \cdot \frac{h}{2} = \frac{h}{2} \cdot A \cdot \rho_{Wasser} \cdot g \cdot \frac{h}{2} = A \cdot \rho_{Wasser} \cdot g \cdot \frac{h^2}{4}$

Mass: $m = A \cdot \rho_{Wasser} \cdot \frac{h}{2} = \frac{2 \cdot E}{g \cdot h}$

Storage Capacity of an Ideal System



Challenges

- Mooring system
- Design of the pumps and turbines
- Design of “large” floating structures

→ use of proven technology!

Concrete Ship

e.g. Construction of the Drogdentunnel and the Öresundtunnel

Challenges

- Mooring system
- Design of the pumps and turbines
- Design of “large” floating structures

→ use of proven technology!

Areas of Application

Possible economical use of *Buoyant Energy* technology

Areas of Application

- Balancing the fluctuations between energy supply and demand
  - Integrating renewable energy into the energy market
  - Use of *Buoyant Energy* as a component of any renewable energy power plant (“Floating Wind Turbine”)
- Peaking power market
- Use in combination with off-grid electrical supply systems
  - Especially applicable to natural and artificial islands

Outlook

Future scientific work

Outlook

- Examination of economic efficiency
  - Highly dependent on future political changes (future standardized tariffs for the availability of storage capacity)
  - Comparison: Grid expansion ⇔ Storage costs
  - Economic efficiency of combining *Buoyant Energy* with other renewable energy sources
- Design-Study
  - Forms of implementation
  - Construction Methods
  - Materials
  - Plant components

Floating Wind Turbine

- Combination of a wind turbine with a floating energy storage system as a renewable combined power station

Source: http://www.tomorrowisgreener.com

Floating Wind Turbine

Design Assumptions:

- offshore Wind turbine: Capacity P = 2 MW
- ideal hydraulic storage plant (Cylinder)
- energy storage: Storage Capacity E = 1 MWh

h [m]	A [m^2]	Radius R [m]	Weight W [to]
20	3669.7	19.3	36 697
30	1631.0	12.9	24 465
40	917.4	9.6	18 349
50	587.2	7.7	14 679
60	407.7	6.4	12 232
70	299.6	5.5	10 485
80	229.4	4.8	9 174
90	181.2	4.3	8 155
100	146.8	3.9	7 339

Floating Wind Turbine

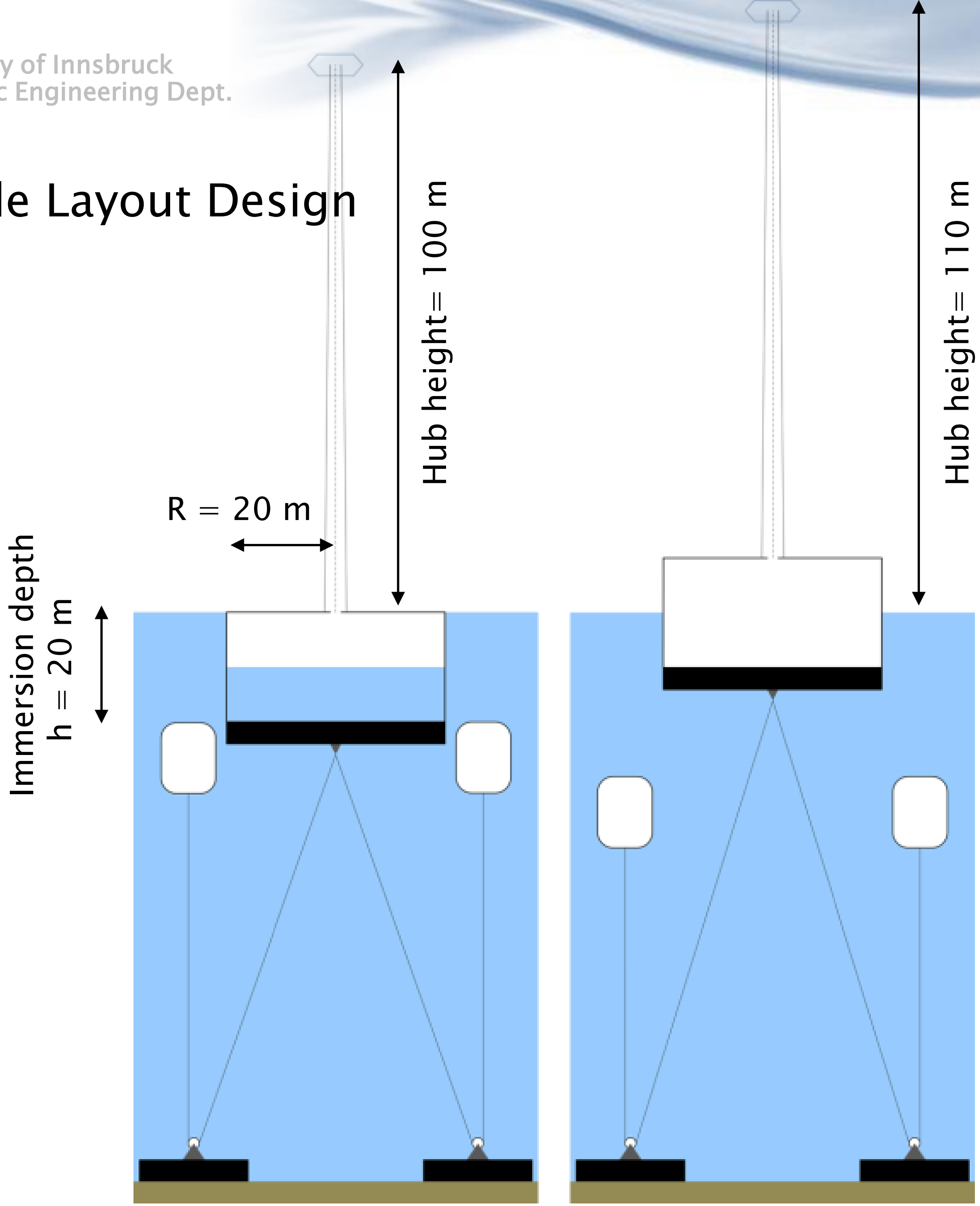
Design Assumptions:

- offshore Wind turbine: Capacity P = 2 MW
- ideal hydraulic storage plant (Cylinder)
- energy storage: Storage Capacity E = 1 MWh

h [m]	A [m^2]	Radius R [m]	Weight W [to]
20	3669.7	19.3	36 697
30	1631.0	12.9	24 465
40	917.4	9.6	18 349
50	587.2	7.7	14 679
60	407.7	6.4	12 232
70	299.6	5.5	10 485
80	229.4	4.8	9 174
90	181.2	4.3	8 155
100	146.8	3.9	7 339

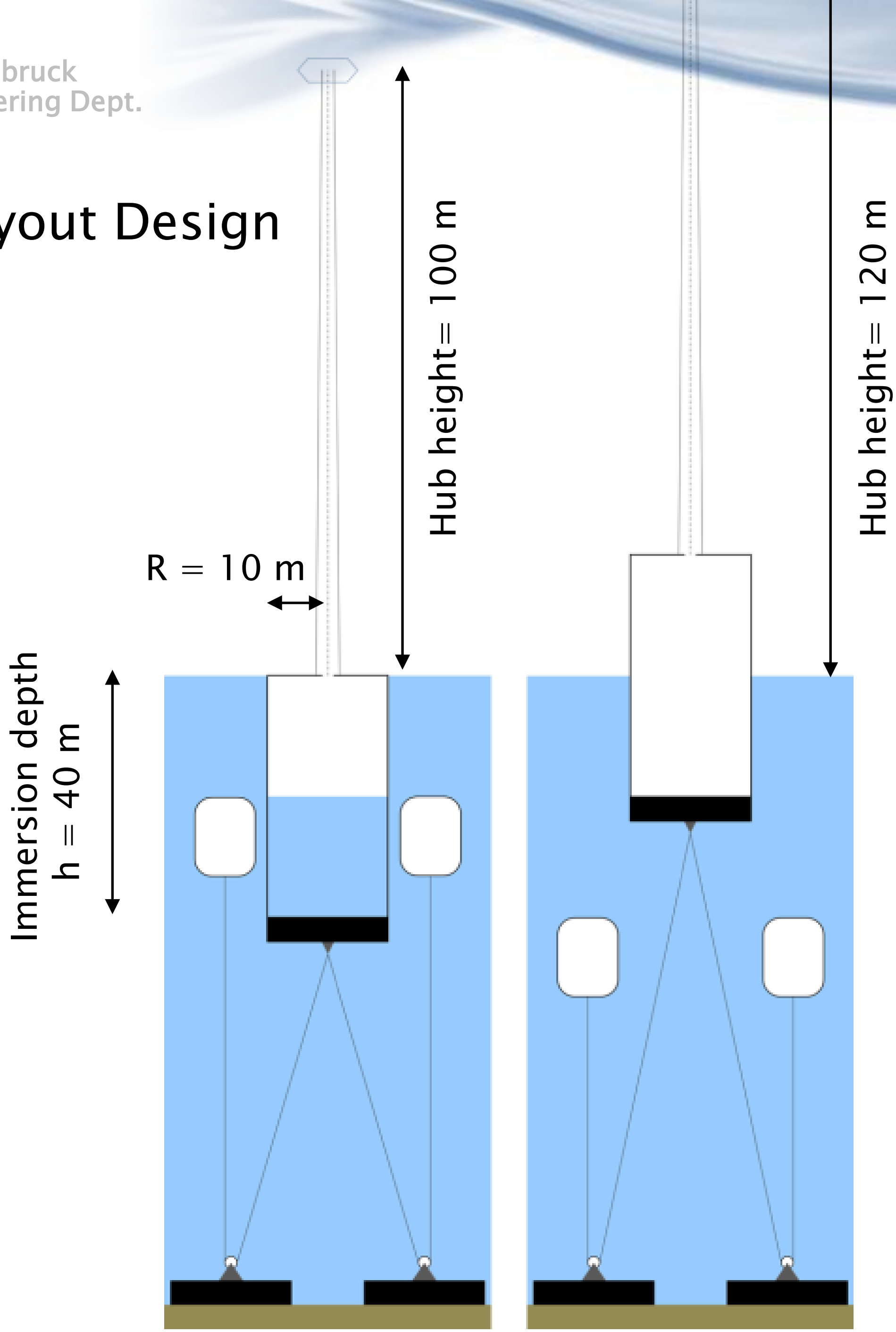
Floating Wind Turbine

Possible Layout Design



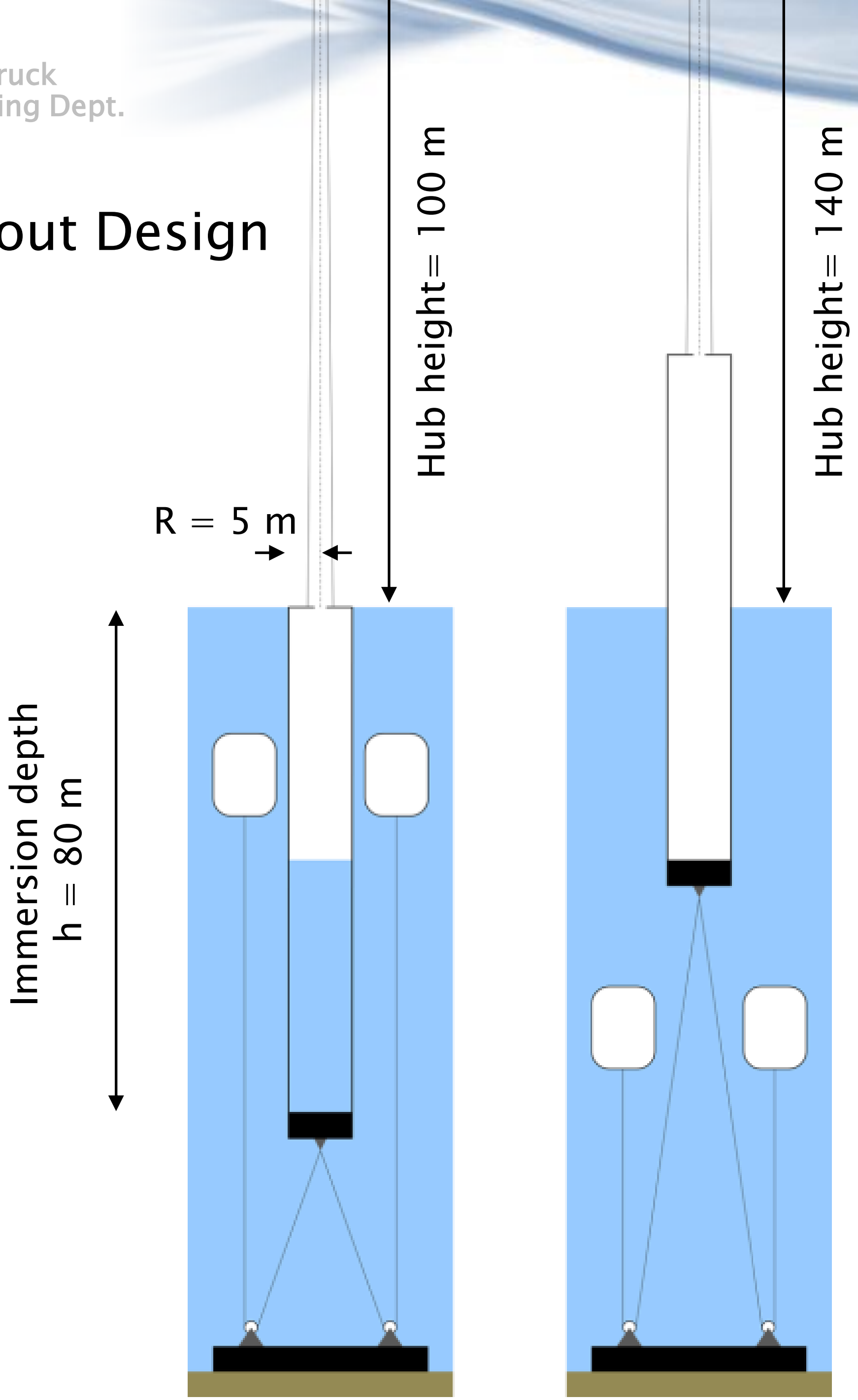
Floating Wind Turbine

Possible Layout Design



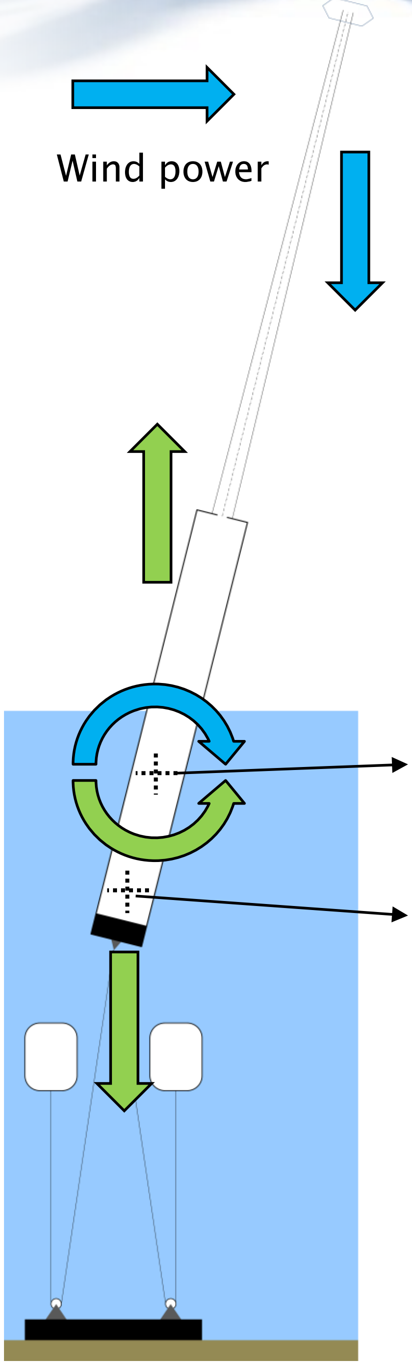
Floating Wind Turbine

Possible Layout Design



Floating Wind Turbine

Floatation Stability



Wind power

Gravitational Force

Tilting torque

Righting moment

Center of buoyancy:
Centroid of volume of immersed part

Center of gravity:

Weight of stabilizing load
+
Buoyant force due to type of anchorage

Floating Wind Turbine

- Advantages
  - ➢ Standardized production
  - ➢ No elaborate flotation devices
  - ➢ Simple maintenance and service
  - ➢ Significant storage capacity when placed in clusters
  - ➢ Location in the water is irrelevant (no limits to water depth)

Hywind – slender cylinder concept

…example for a visionary *Floating Wind Turbine* – concept. However there is no storage device integrated into the design!

SIEMENS

Statoil

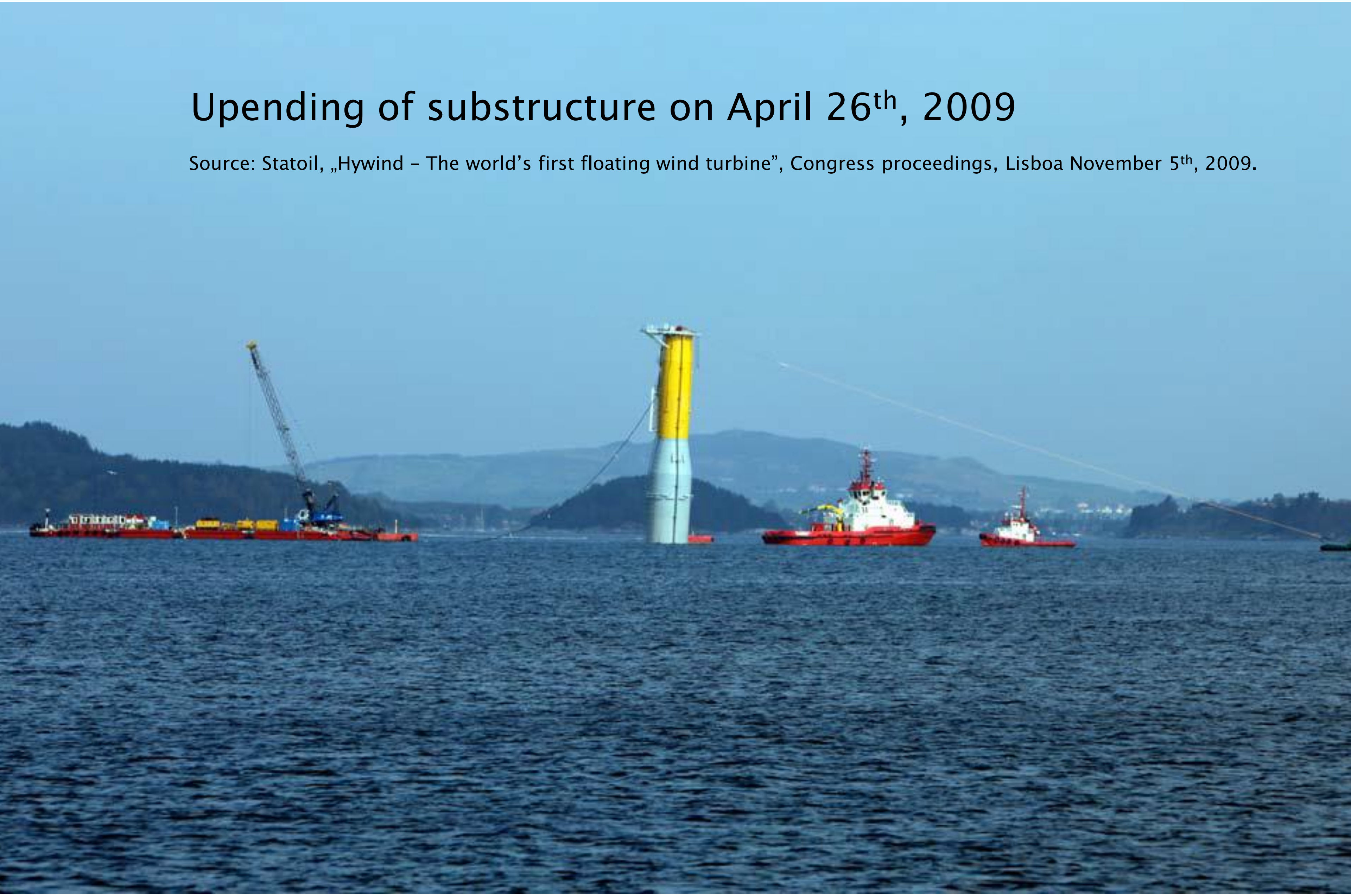
- Main facts about Hywind:
  - Siemens SWT 2.3 MW
  - Turbine weight: 138 tons
  - Draft: 100 m
  - Displacement: 5300 m^3
  - Diameter at water line: 6 m
  - Water depths: 120-700 m
  - one prototype is currently operating near Karmøy, Norway

Åmøyfjorden, April 22nd, 2009

Source: Statoil, „Hywind – The world’s first floating wind turbine”, Congress proceedings, Lisboa November 5th, 2009.

Upending of substructure on April 26th, 2009

Source: Statoil, „Hywind – The world’s first floating wind turbine”, Congress proceedings, Lisboa November 5th, 2009.



Official opening September 8th, 2009

Source: Statoil, „Hywind – The world’s first floating wind turbine”, Congress proceedings, Lisboa November 5th, 2009.

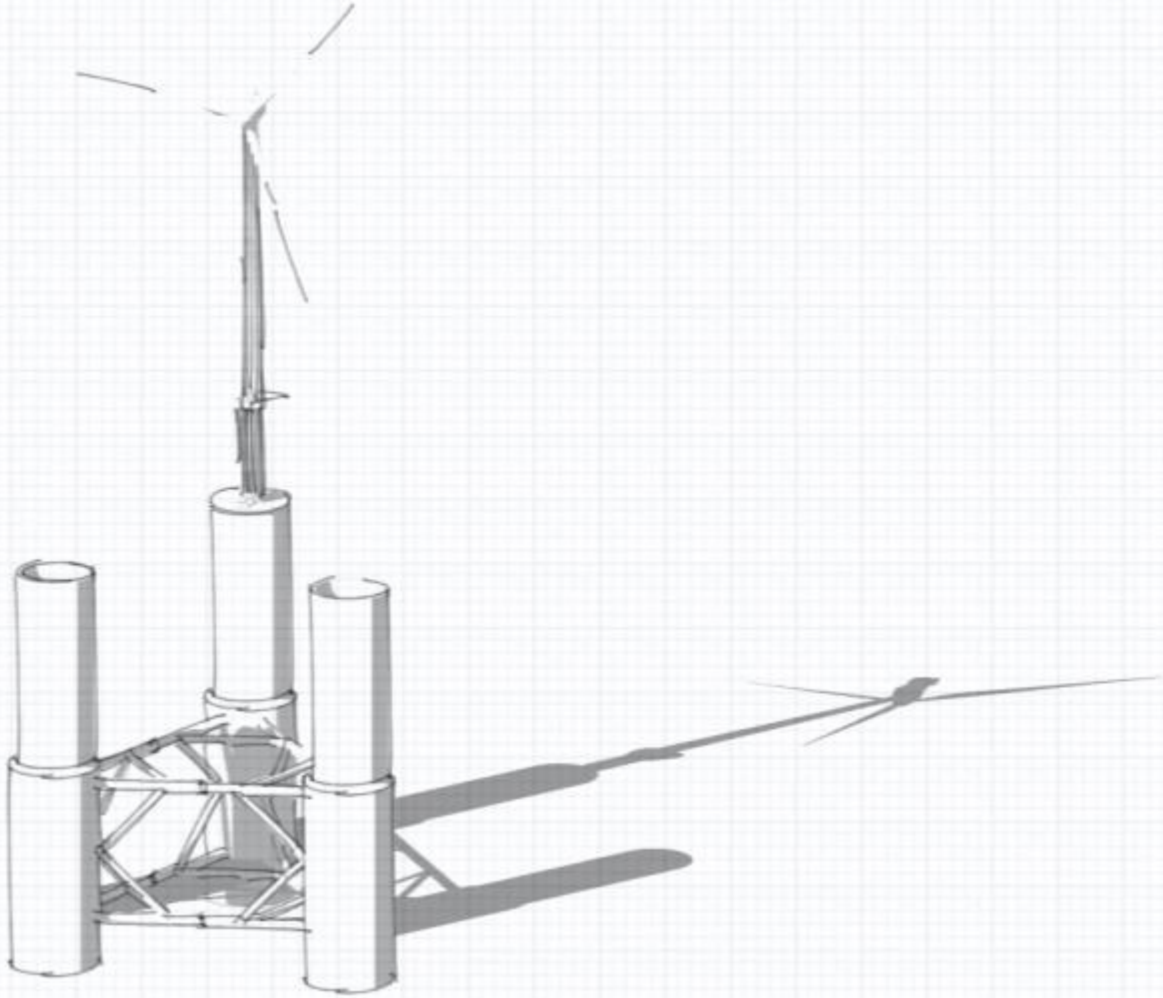
Design–Study
(ongoing Master–Thesis)

- Floating Wind Turbine – WindFloat
- Floating Monopile Cluster

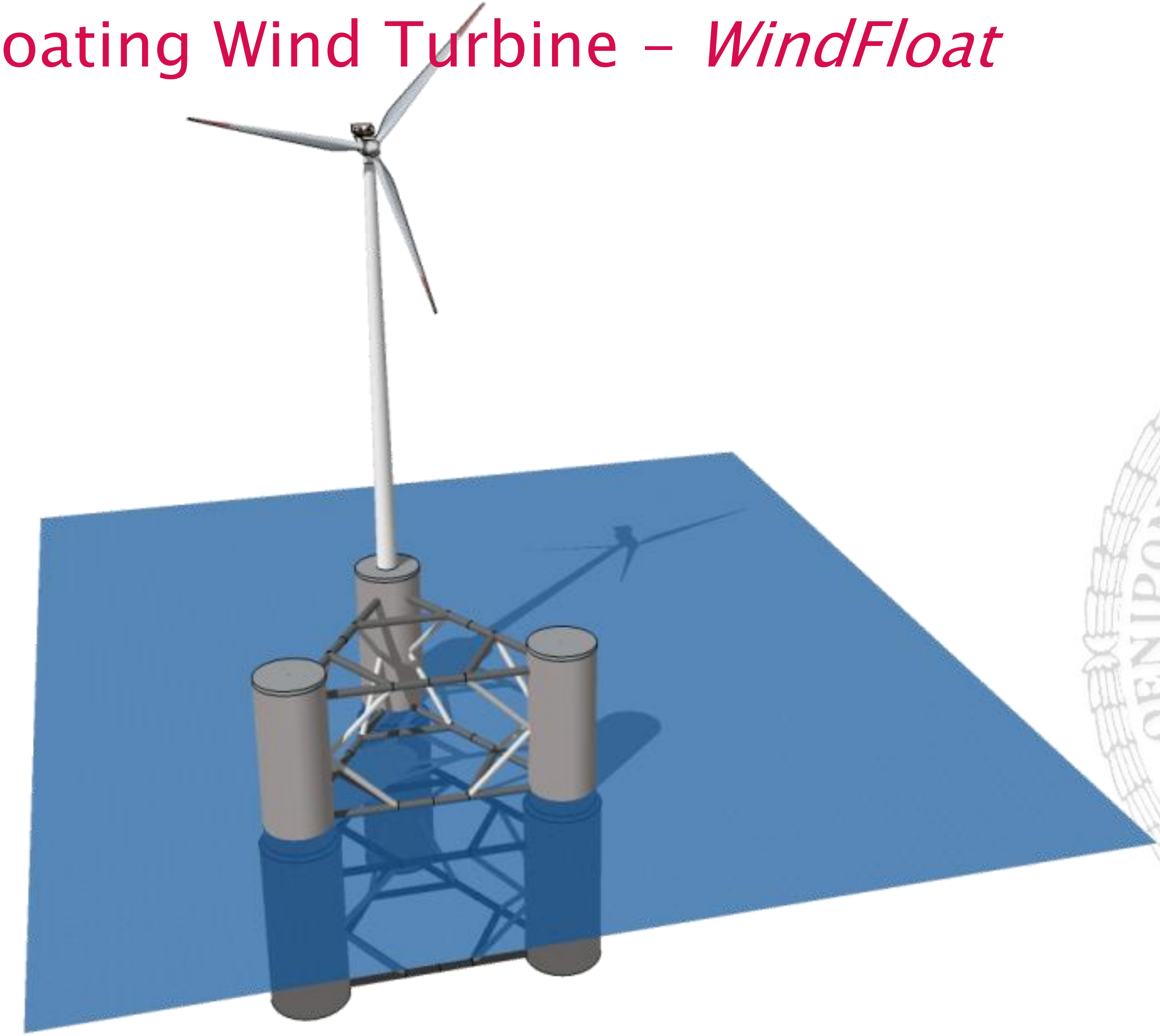
WindFloat-System

Floating Wind Turbine – *WindFloat*

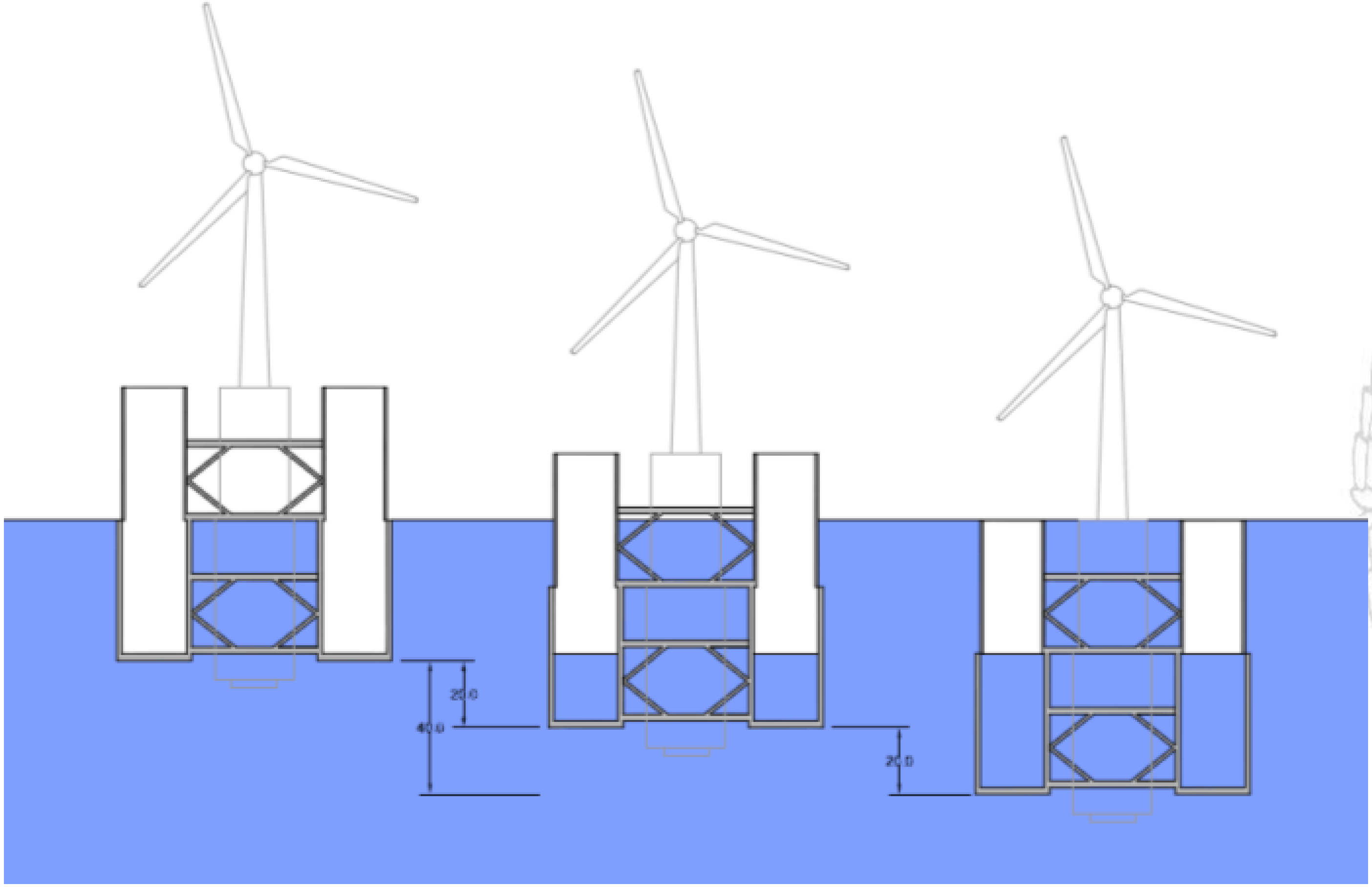
Energy Capacity → 4 MWh



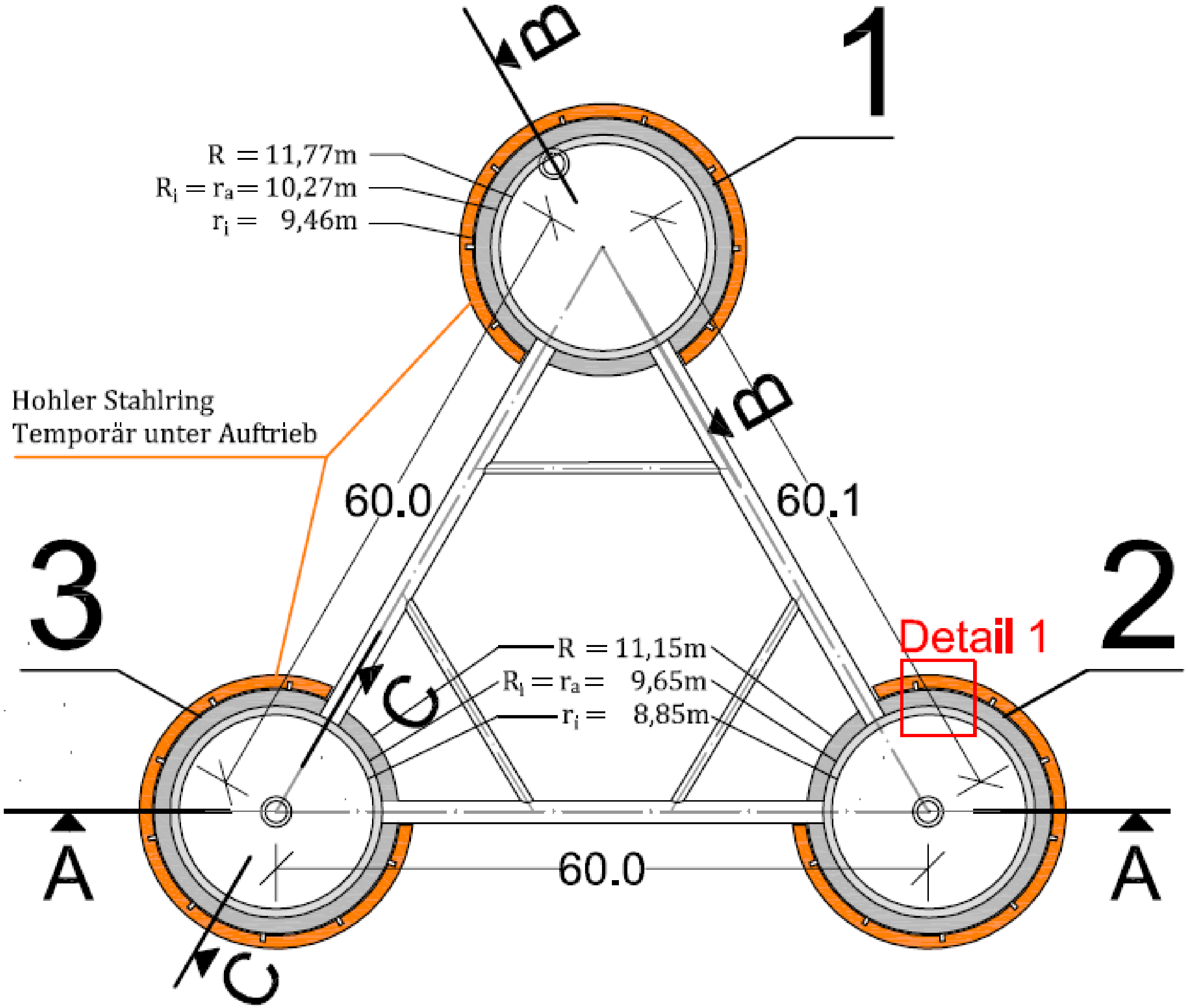
Floating Wind Turbine – *WindFloat*



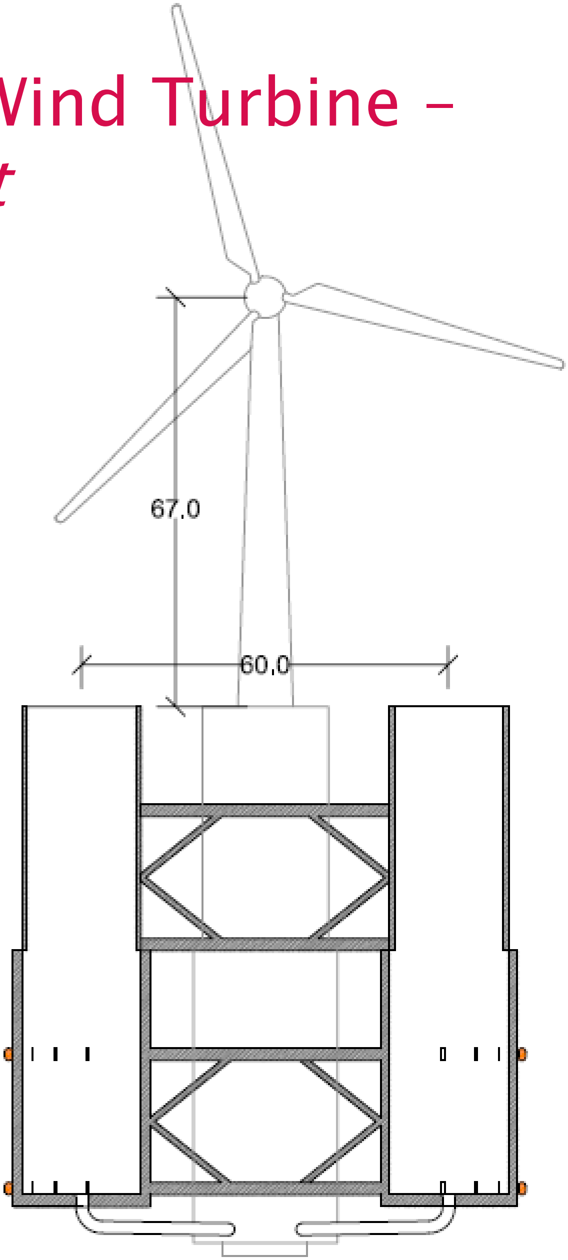
Floating Wind Turbine – *WindFloat*

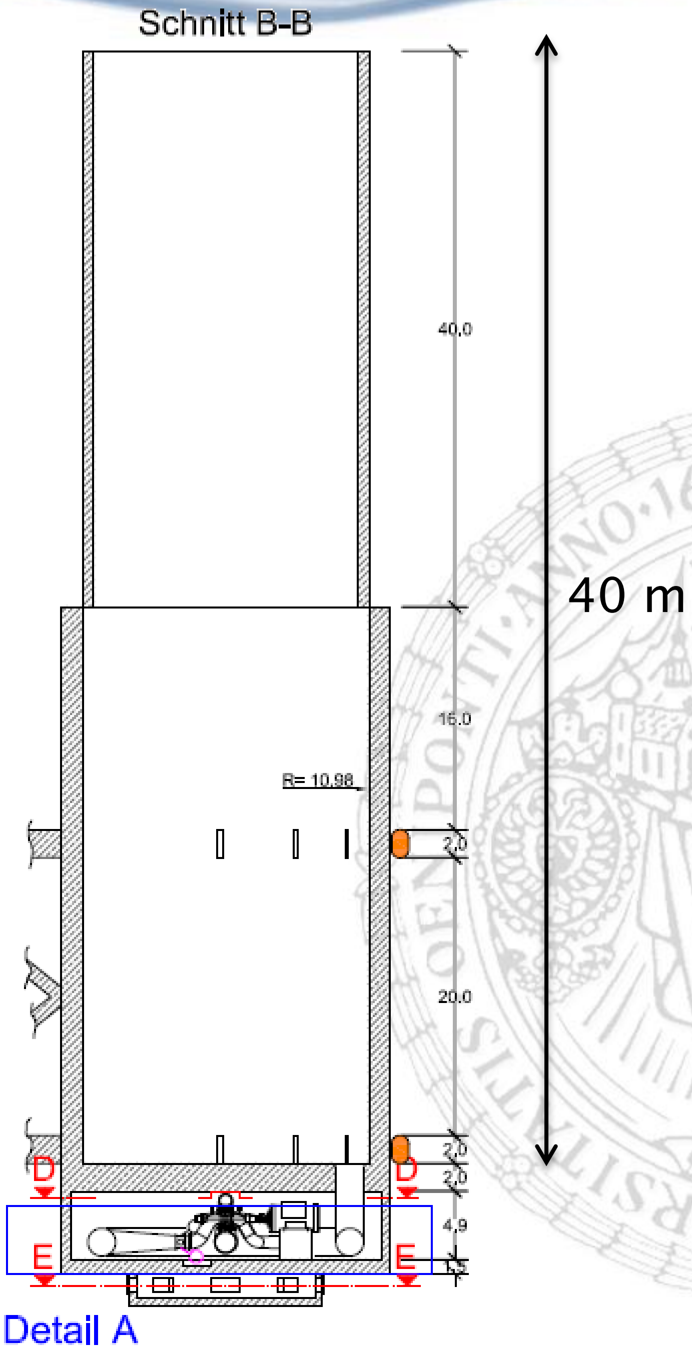


Floating Wind Turbine – *WindFloat*



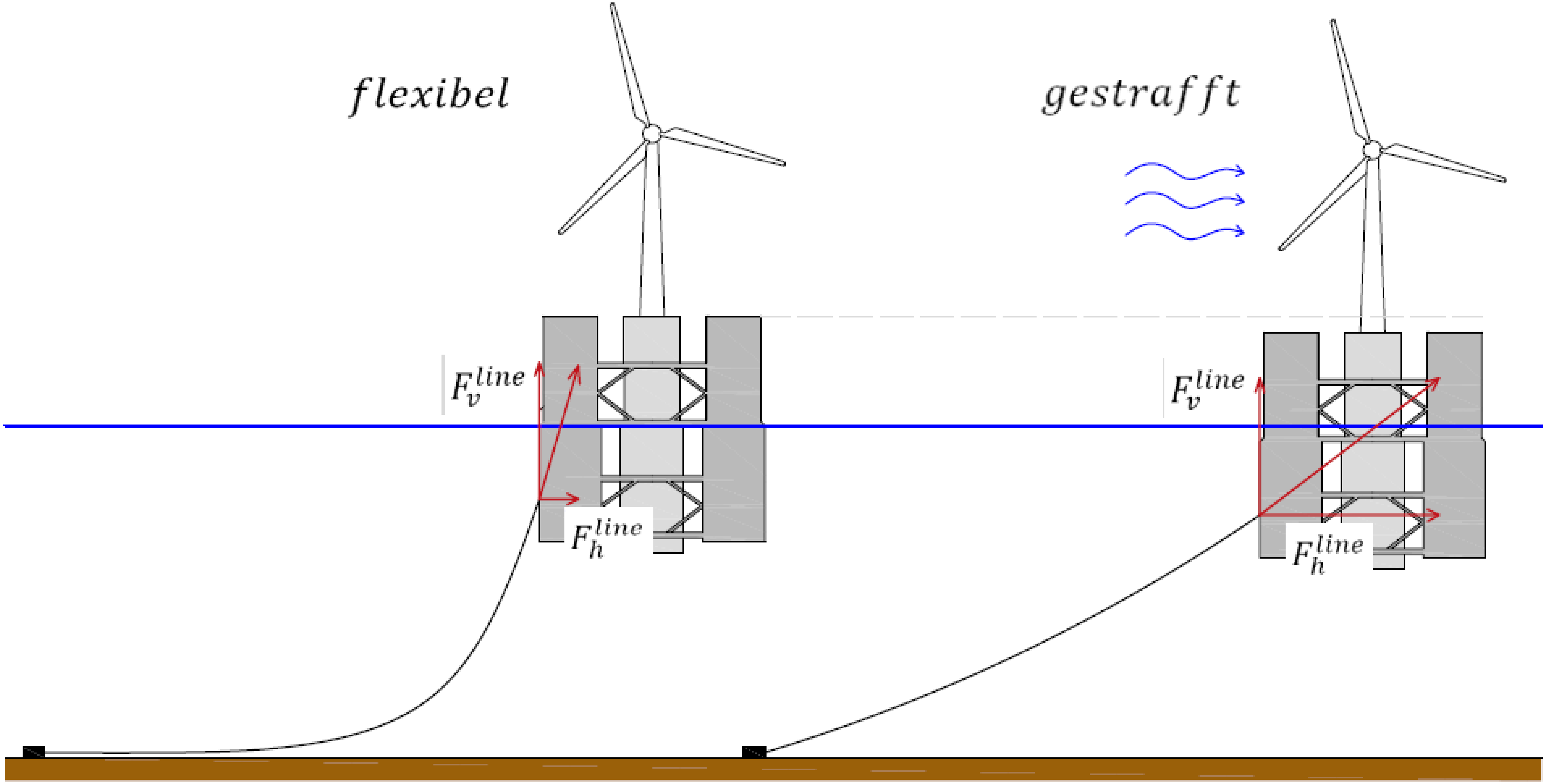
Floating Wind Turbine – *WindFloat*





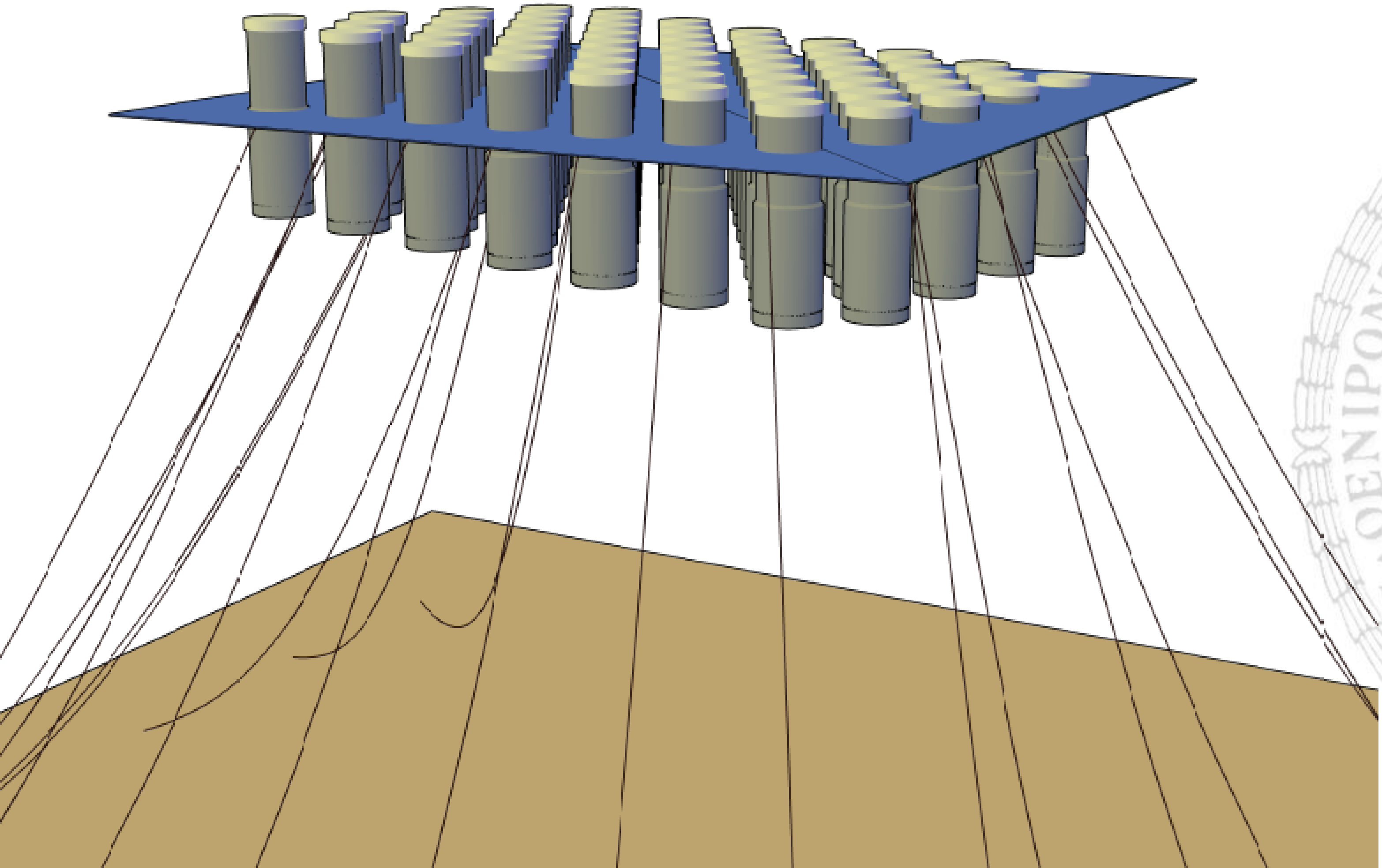
Floating Wind Turbine – *WindFloat*

Mooring System

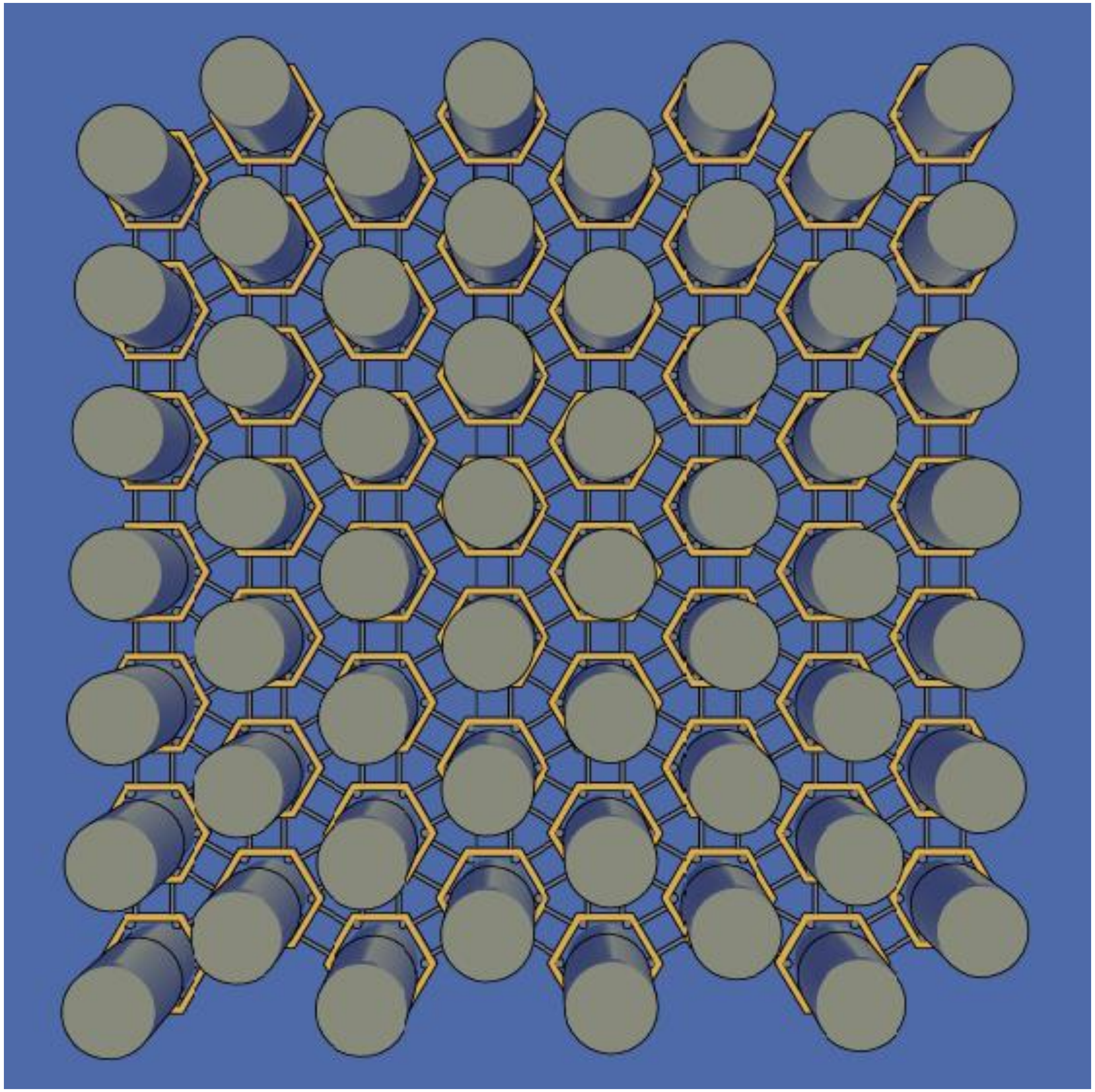


Floating Monopile Cluster

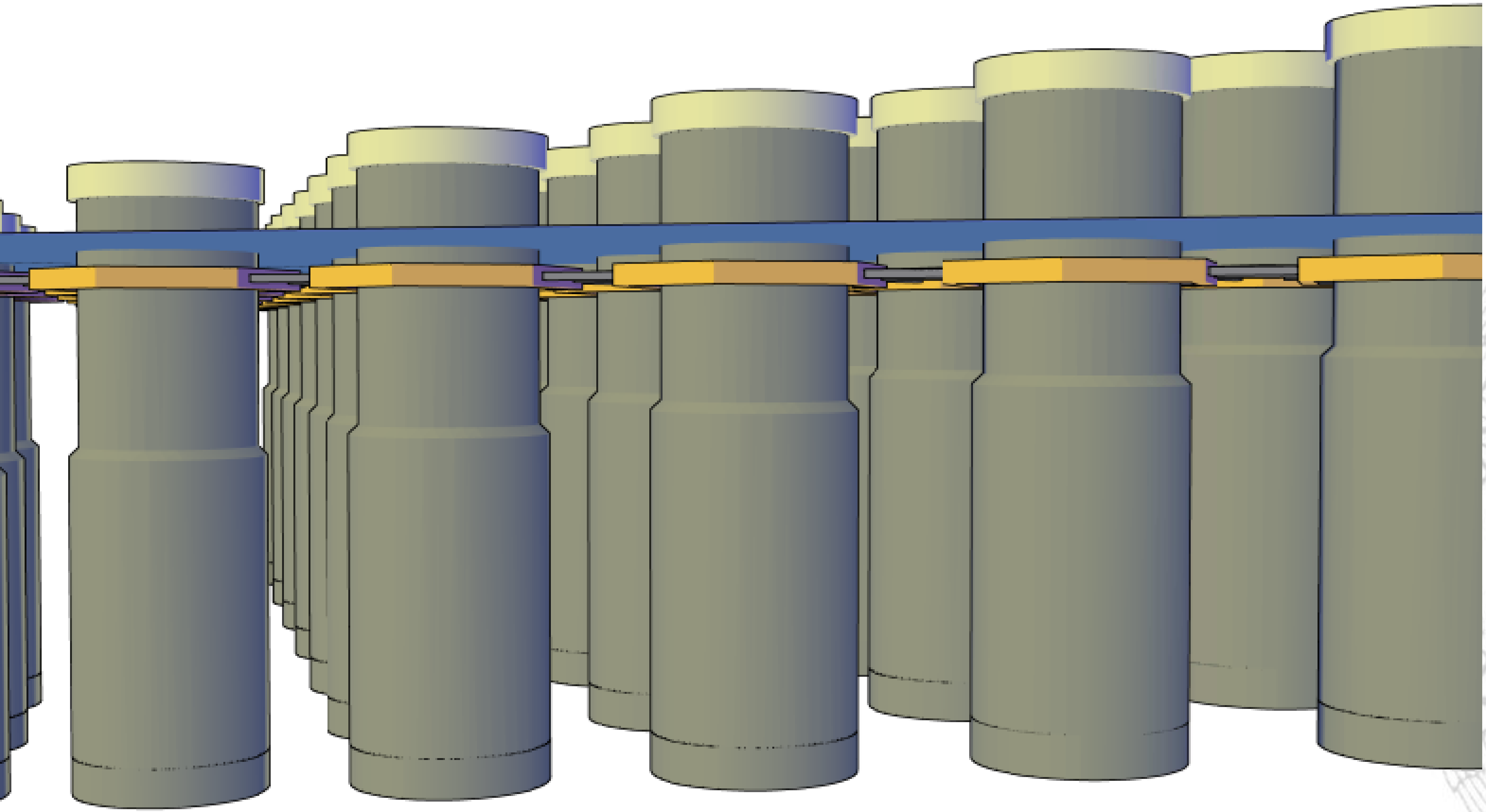
Energy Capacity for 1 Monopile → 2 MWh



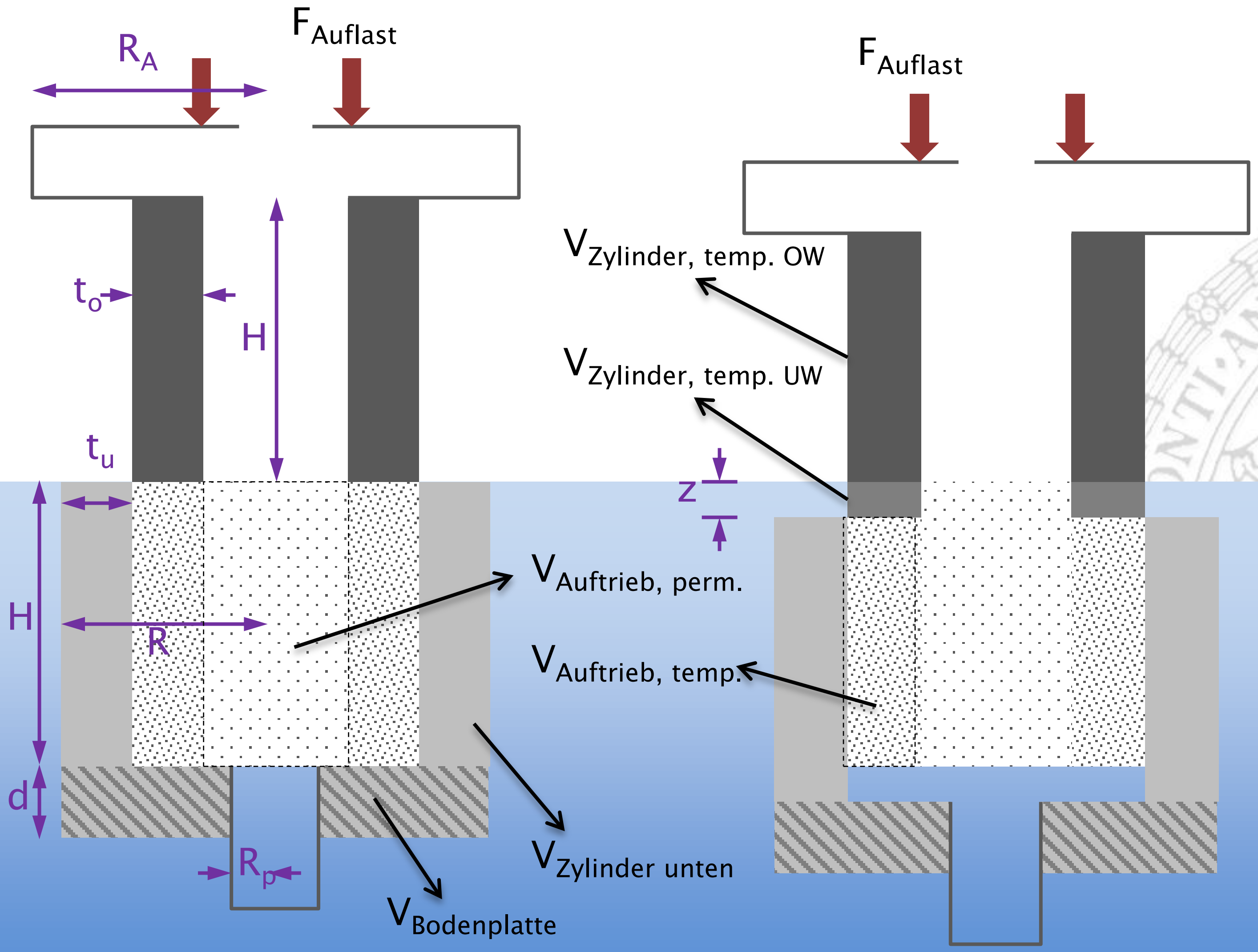
Floating Monopile Cluster



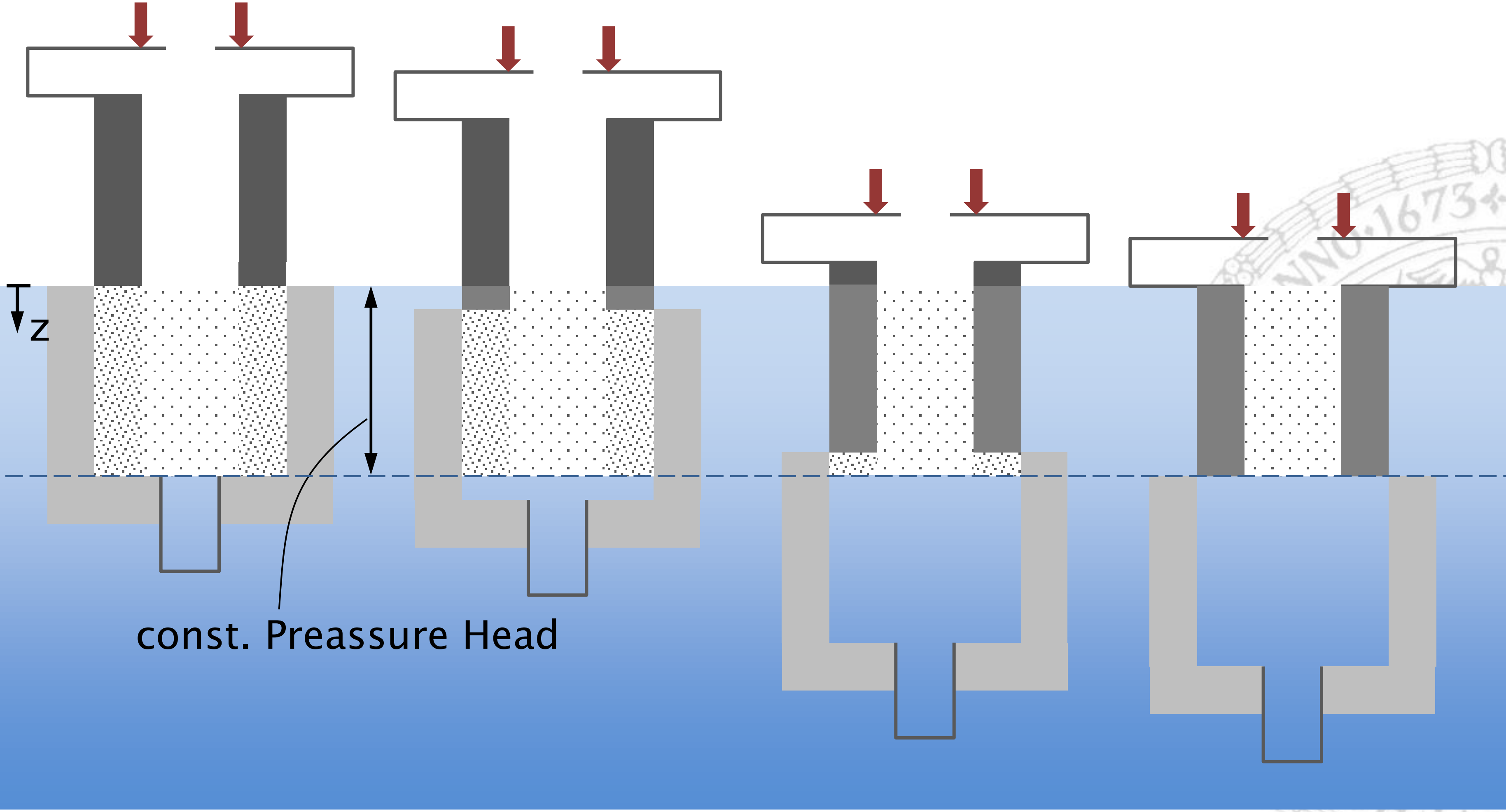
Floating Monopile Cluster



Floating Monopile Cluster



Floating Monopile Cluster



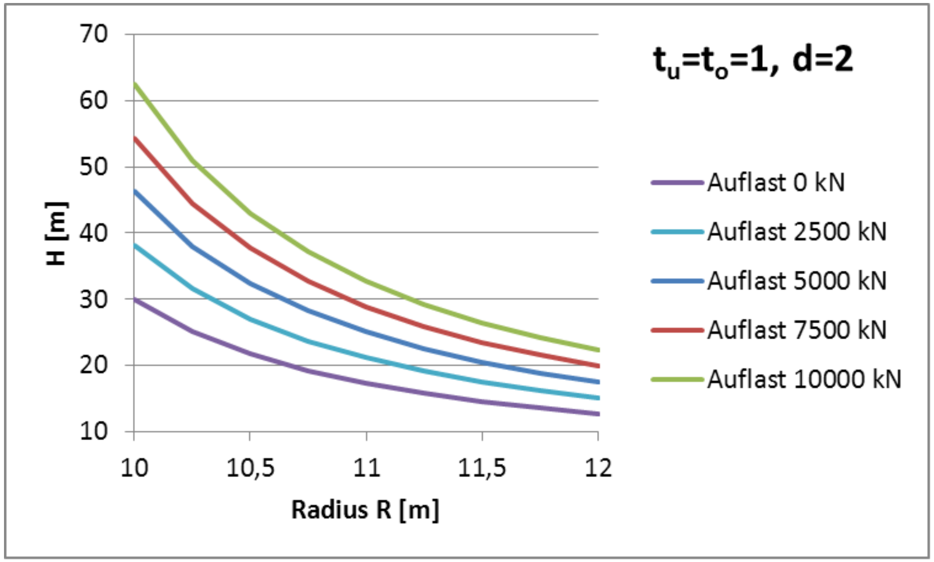
Floating Monopile Cluster

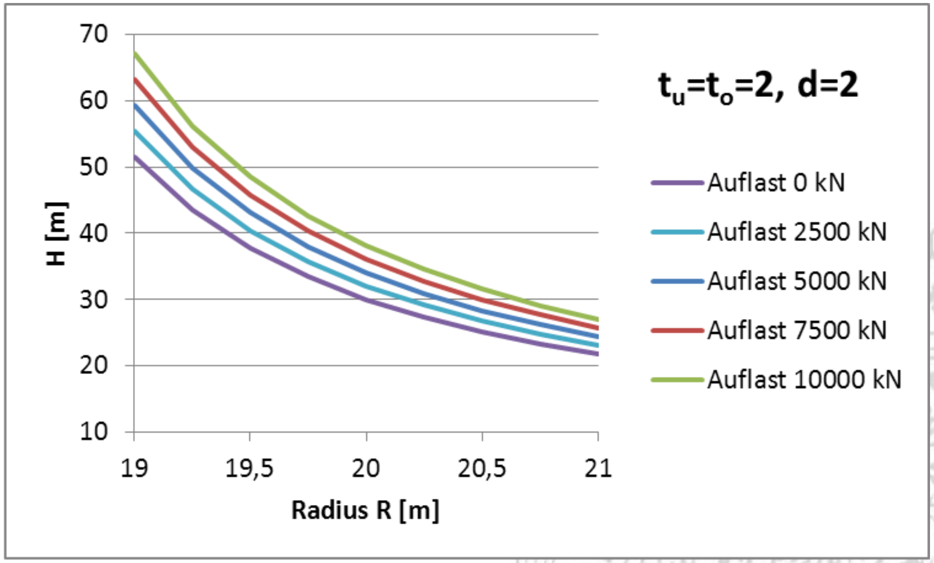
- Design „Formula“

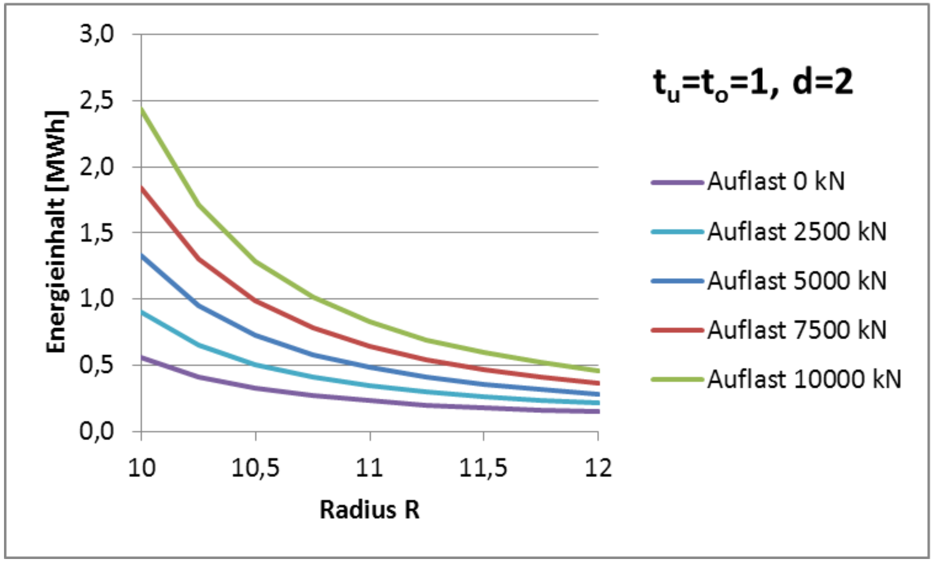
$$(\rho_{Concrete} - \rho_{Water}) \cdot R^2 \cdot (H + d) - \rho_{Concrete} \cdot H \cdot (R - t_u - t_o)^2 + \frac{F_{Auflast}}{\pi \cdot g} = 0$$

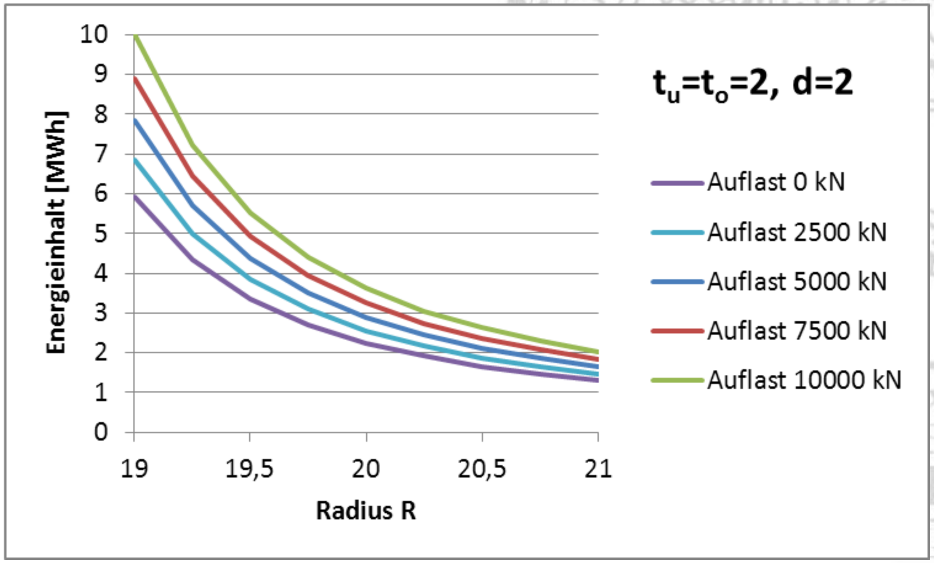
- Energy capacity

$$E_{max} = \eta_{elect.} \cdot \pi \cdot H^2 \cdot (R - t_u)^2 \cdot \rho_{Water} \cdot g$$

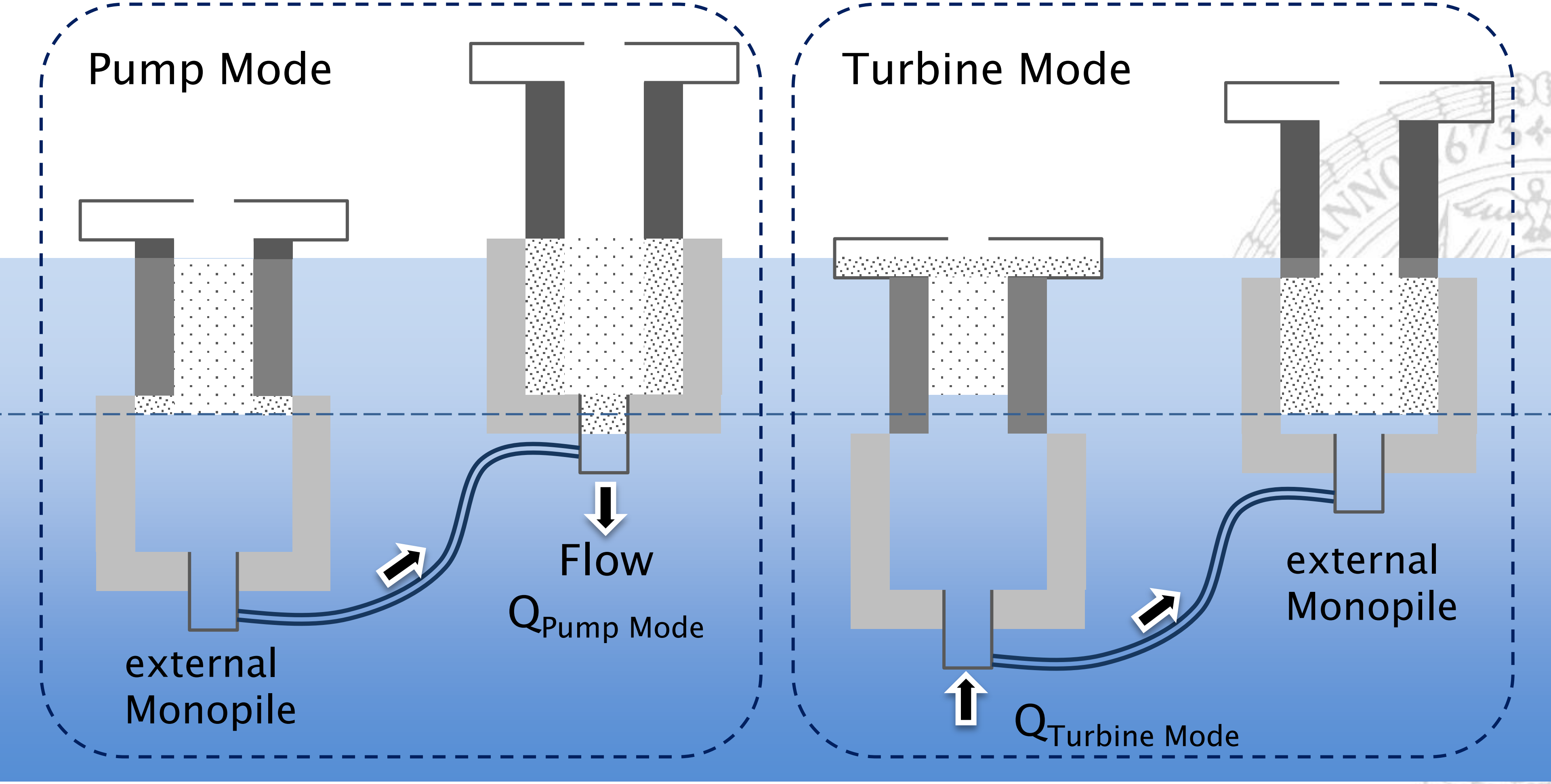

$t_u=t_o=1$, d=2
H [m]
70
60
50
40
30
20
10
10
10,5
11
11,5
12
Radius R [m]
Auflast 0 kN
Auflast 2500 kN
Auflast 5000 kN
Auflast 7500 kN
Auflast 10000 kN


$t_u=t_o=2$, d=2
H [m]
70
60
50
40
30
20
10
19
19,5
20
20,5
21
Radius R [m]
Auflast 0 kN
Auflast 2500 kN
Auflast 5000 kN
Auflast 7500 kN
Auflast 10000 kN

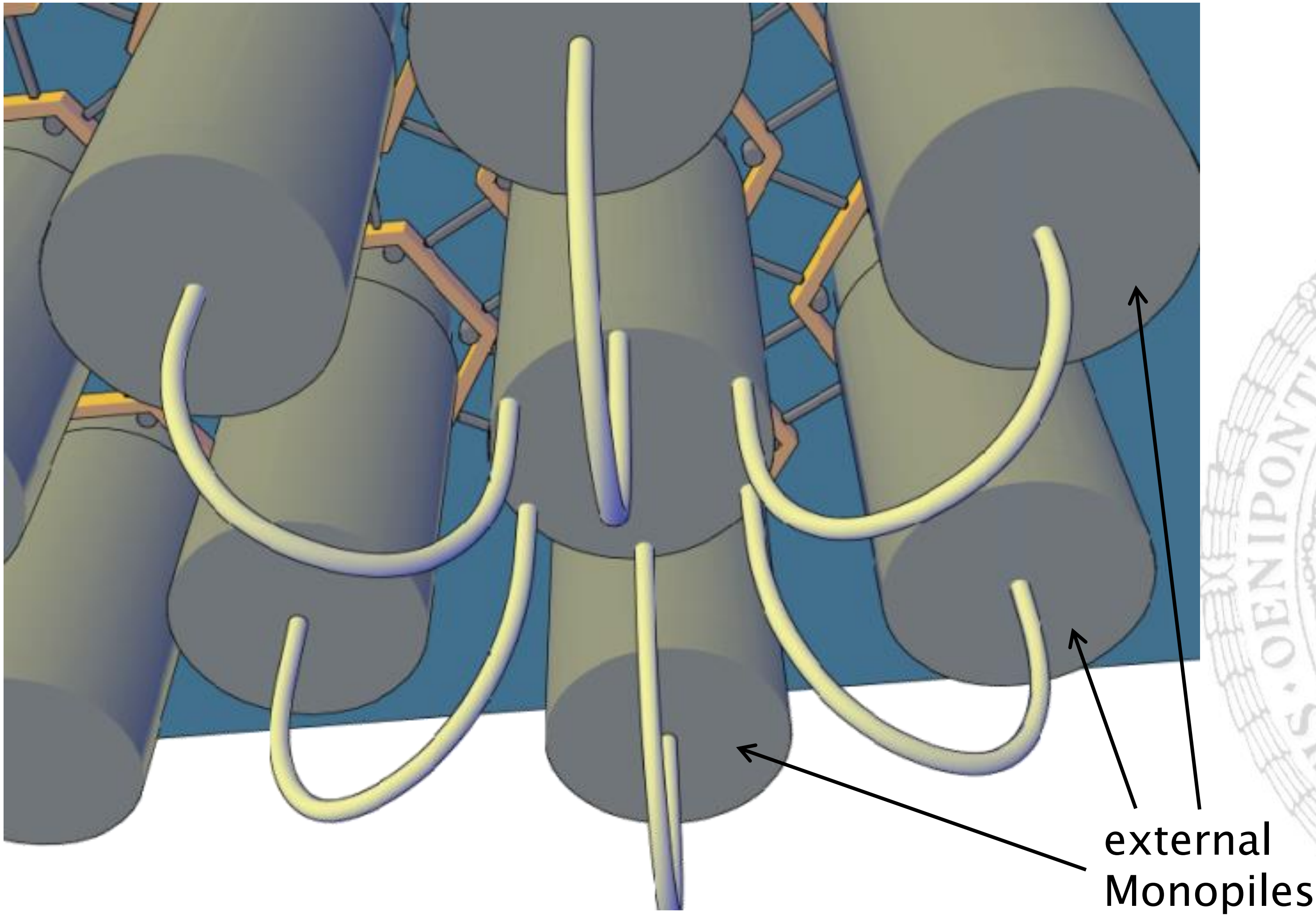

$t_u=t_o=1$, d=2
Energieinhalt [MWh]
3,0
2,5
2,0
1,5
1,0
0,5
0,0
10
10,5
11
11,5
12
Radius R
Auflast 0 kN
Auflast 2500 kN
Auflast 5000 kN
Auflast 7500 kN
Auflast 10000 kN


$t_u=t_o=2$, d=2
Energieinhalt [MWh]
10
9
8
7
6
5
4
3
2
1
0
19
19,5
20
20,5
21
Radius R
Auflast 0 kN
Auflast 2500 kN
Auflast 5000 kN
Auflast 7500 kN
Auflast 10000 kN

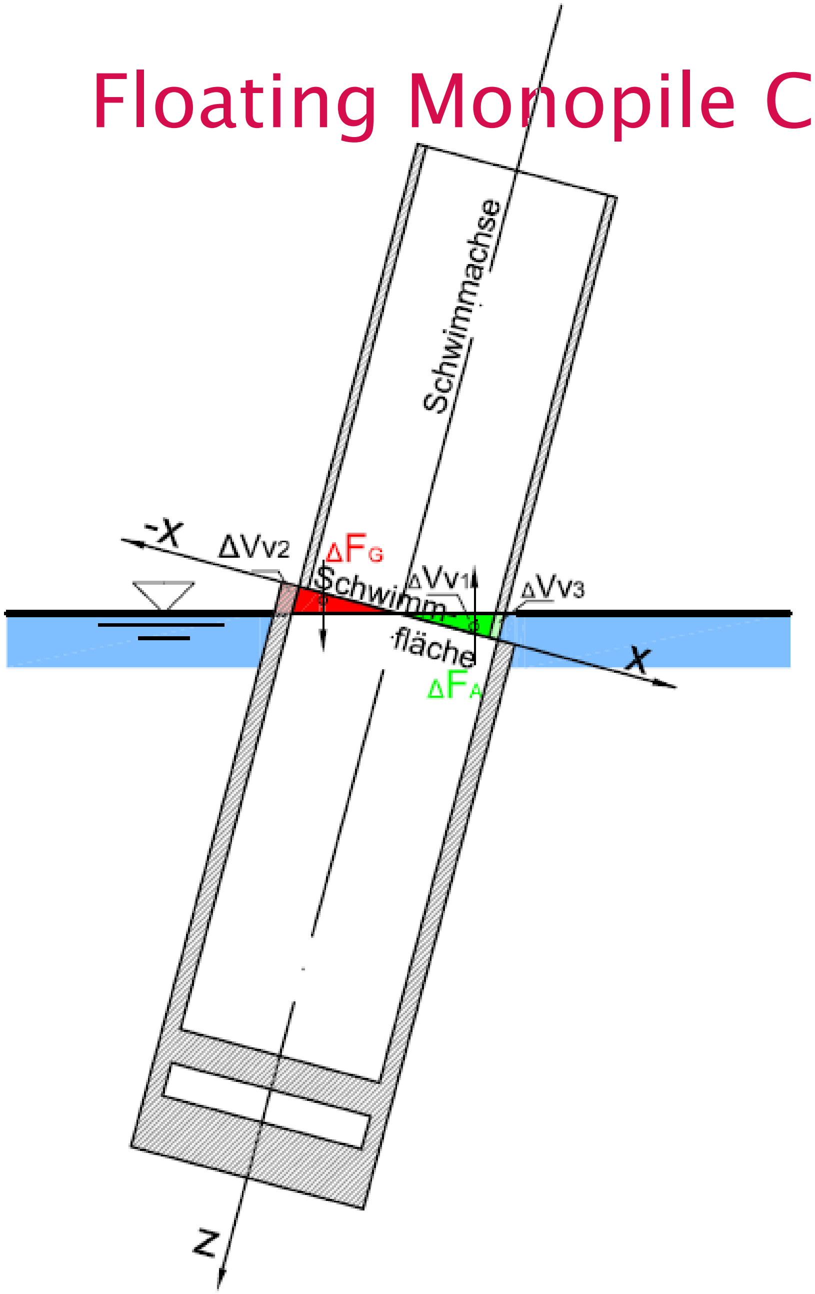
Floating Monopile Cluster

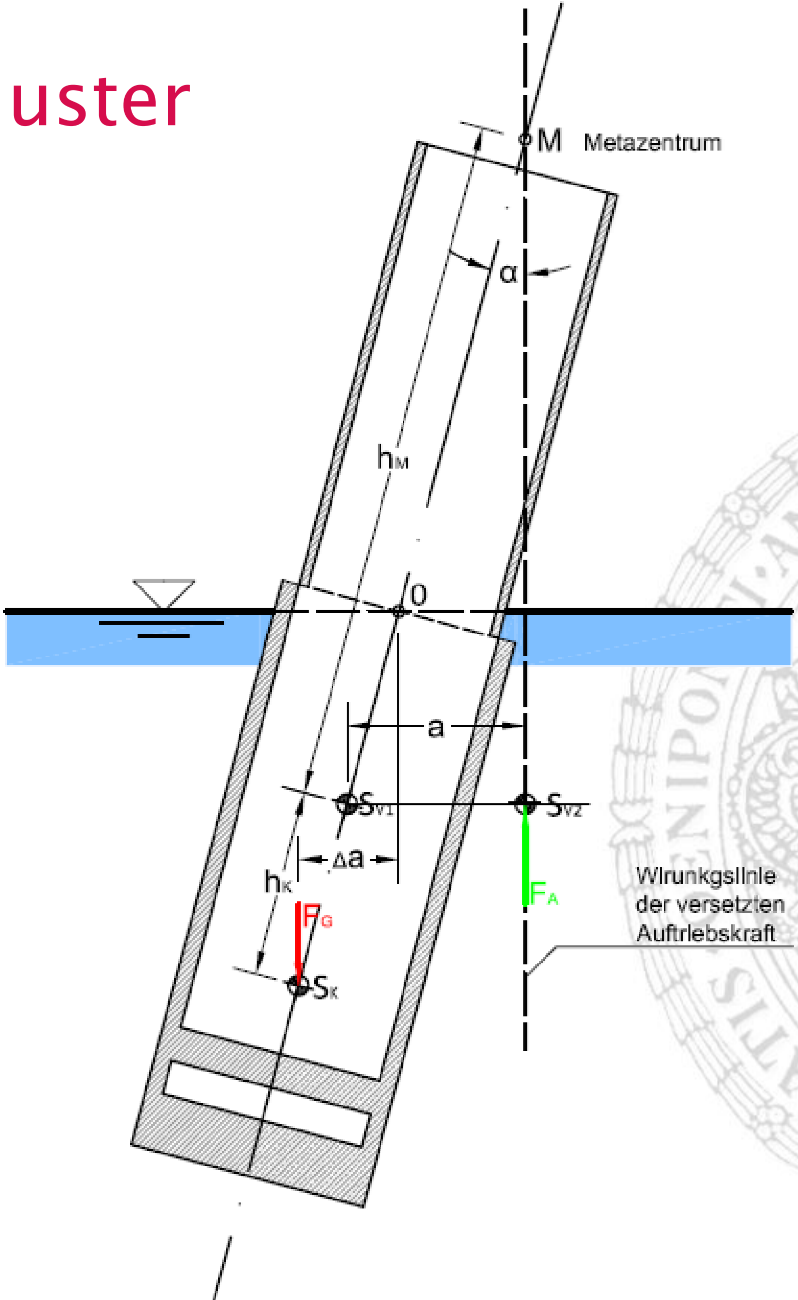


Floating Monopile Cluster



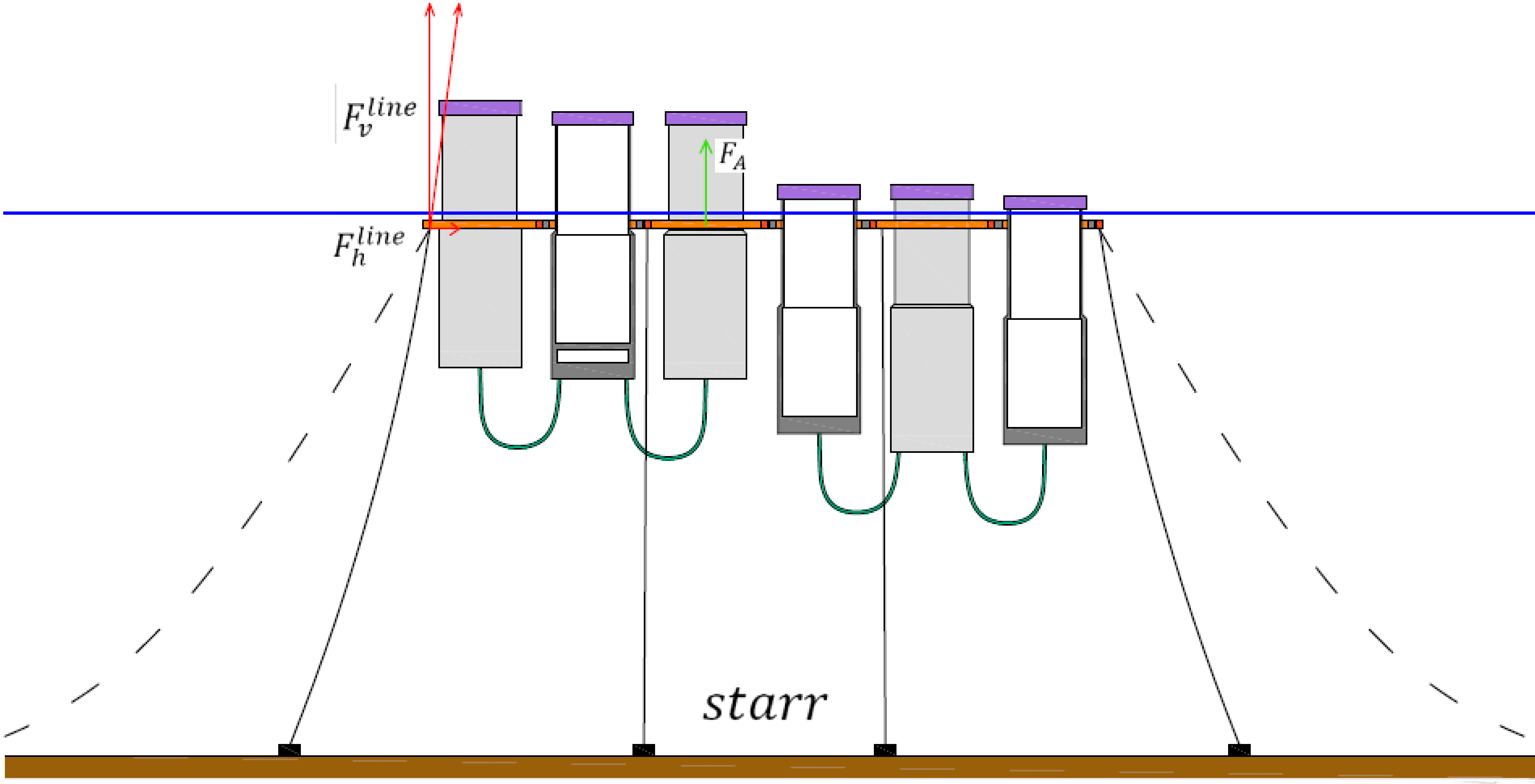
Floating Monopile Cluster





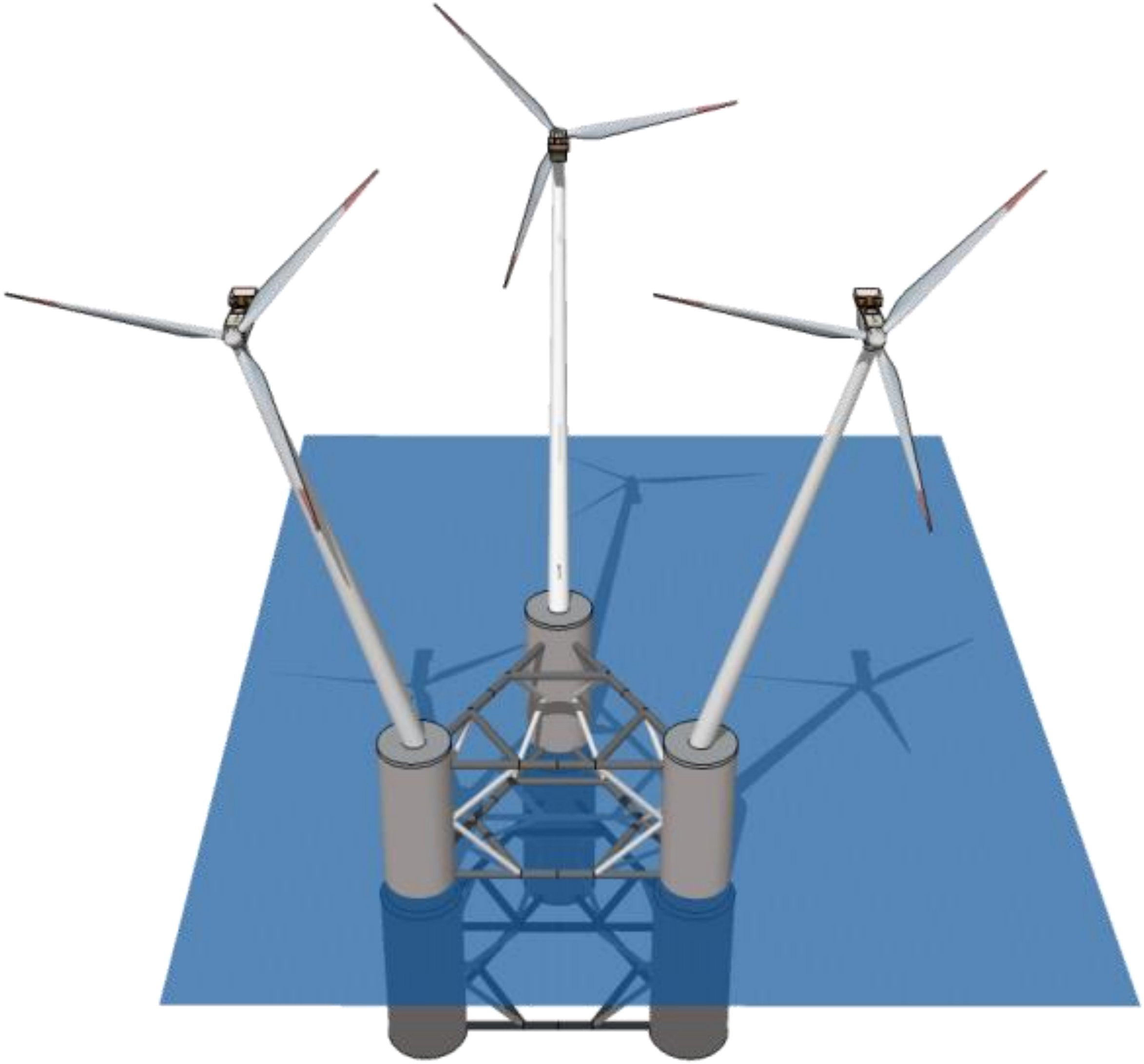
Floating Monopile Cluster

Mooring System

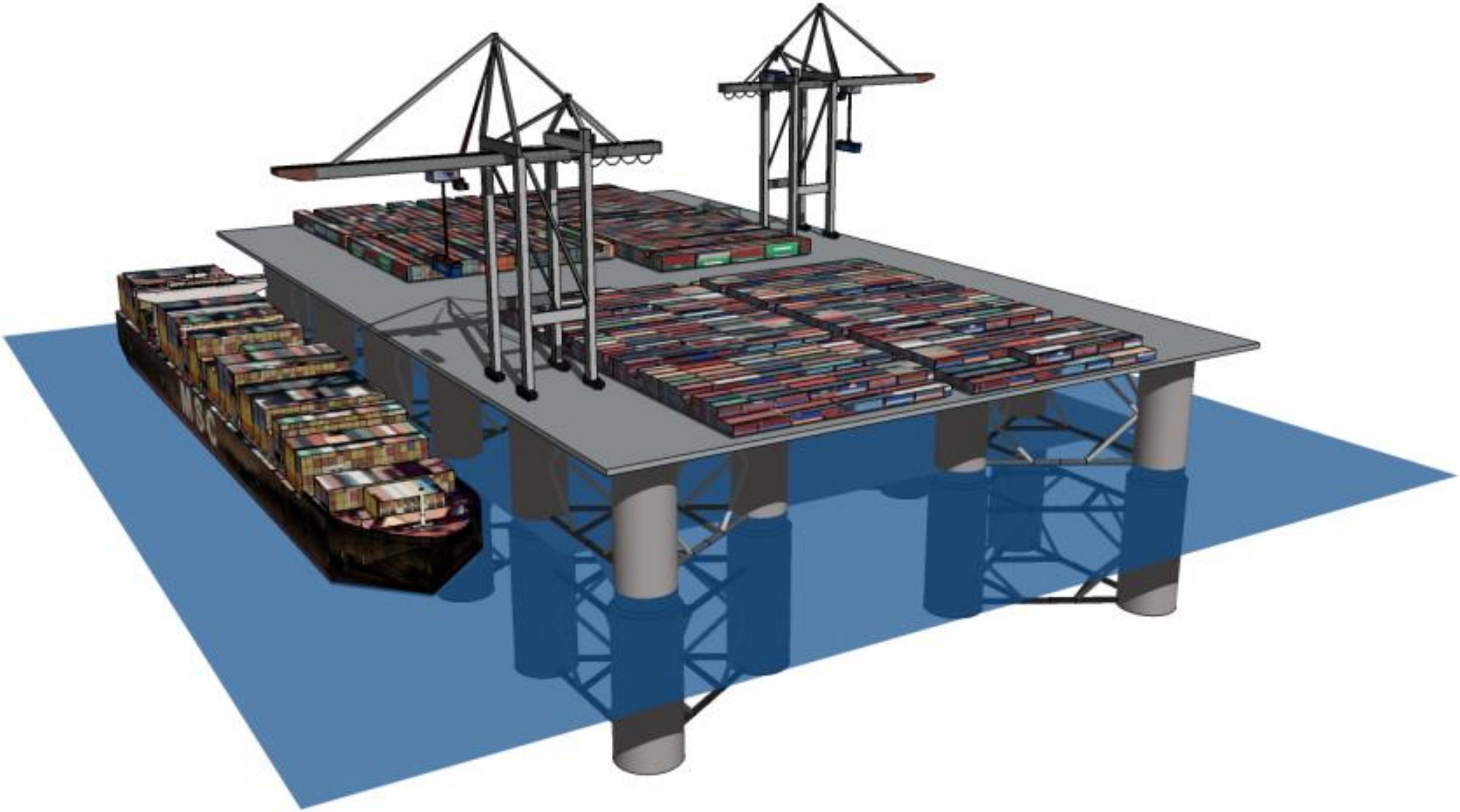


Floating Wind Turbine

3 x 2.3 MW-Windturbines (WindSea Concept)



Floating Container Port



BUOYANT ENERGY
smart concepts for energy storage

meets

THE SEASTEADING INSTITUTE

BUOYANT ENERGY
smart concepts for energy storage

meets

THE SEASTEADING INSTITUTE

BUOYANT ENERGY
smart concepts for energy storage

meets

THE SEASTEADING INSTITUTE

BUOYANT ENERGY
smart concepts for energy storage

meets

THE SEASTEADING INSTITUTE

BUOYANT ENERGY
smart concepts for energy storage

meets

THE SEASTEADING INSTITUTE

BUOYANT ENERGY
smart concepts for energy storage

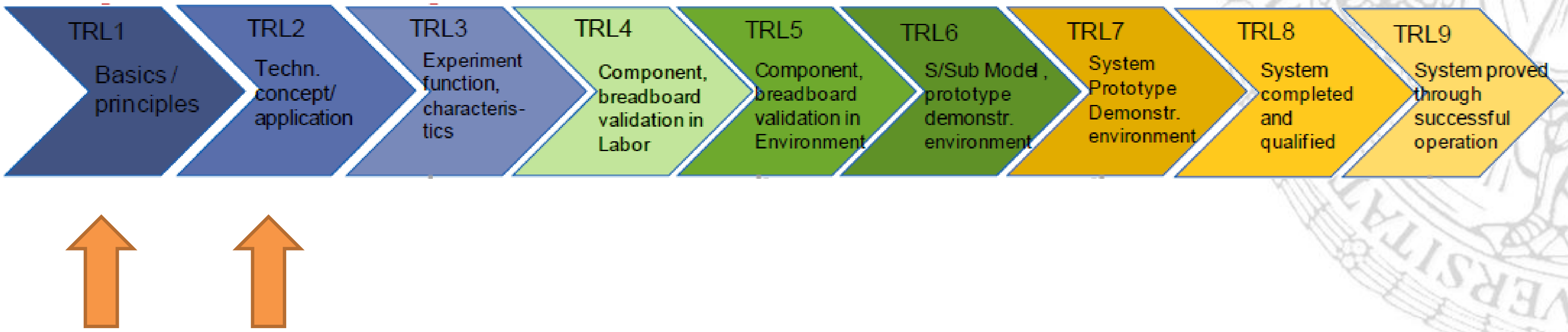
meets

THE SEASTEADING INSTITUTE

National Research Funding

e!Missi0n+.at
Energy Mission Austria

Technology Readiness Levels according to the US Department of Energy



- TRL1 Basics / principles
- TRL2 Techn. concept/ application
- TRL3 Experiment function, characteris-tics
- TRL4 Component, breadboard validation in Labor
- TRL5 Component, breadboard validation in Environment
- TRL6 S/Sub Model , prototype demonstr. environment
- TRL7 System Prototype Demonstr. environment
- TRL8 System completed and qualified
- TRL9 System proved through successful operation

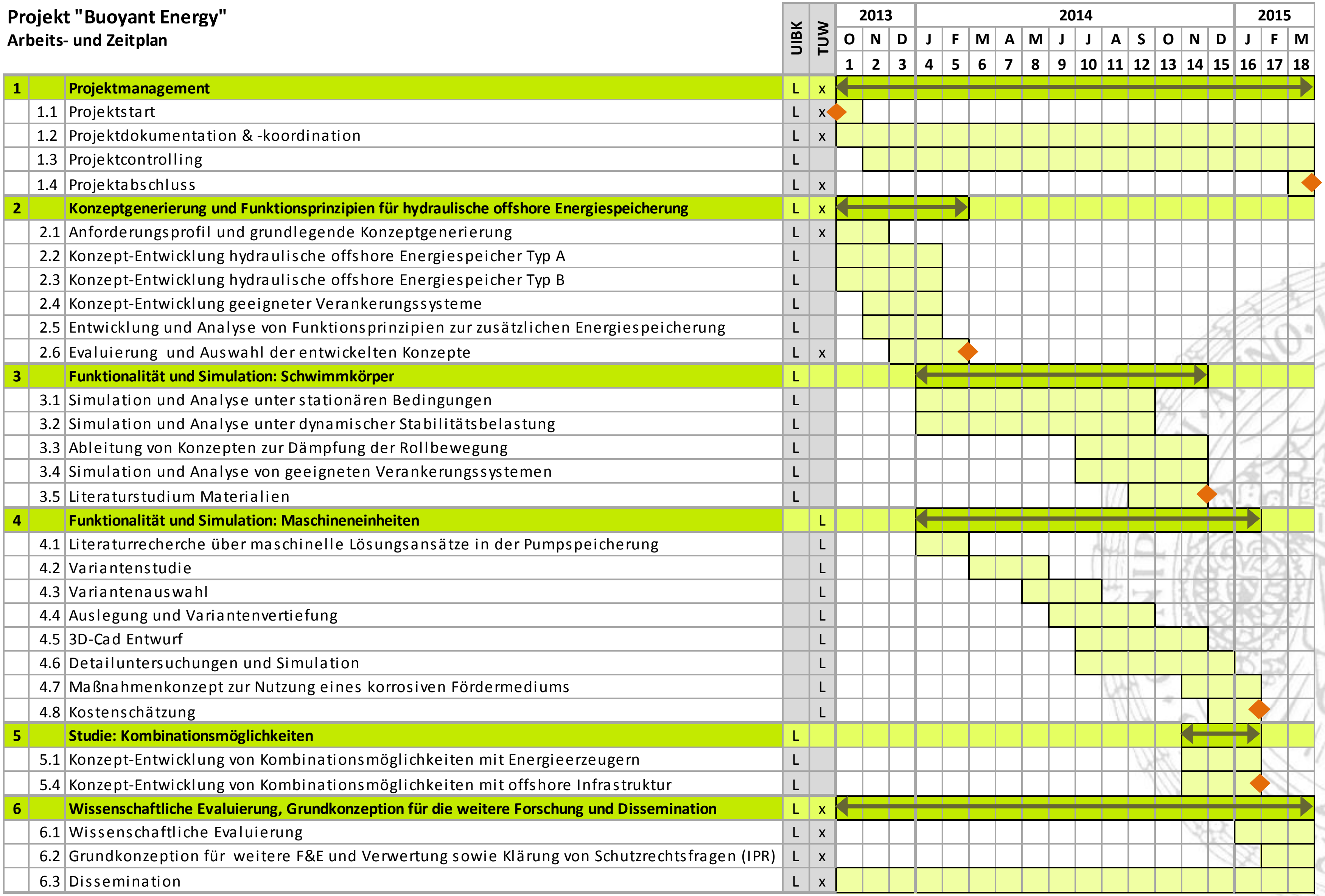
National Research Funding

- Project Synopsis

Buoyant Energy allows storing electrical energy in lakes and oceans, next to offshore wind turbines. Thus, an important contribution to the integration of volatile, renewable energies could be achieved. The transfer of well-known pump-storage principle into a challenging, highly dynamic environment requires important fundamental research and development activities based on Austrian core competencies.

Projekt "Buoyant Energy"

Arbeits- und Zeitplan



			UIBK	TUW	2013			2014												2015		
					O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		**Projektmanagement**	L	x	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔
	1.1	Projektstart	L	x	◆■																	
	1.2	Projektdokumentation & -koordination	L	x	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	1.3	Projektcontrolling	L			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	1.4	Projektabschluss	L	x																		■◆
2		**Konzeptgenerierung und Funktionsprinzipien für hydraulische offshore Energiespeicherung**	L	x	↔	↔	↔	↔	↔													
	2.1	Anforderungsprofil und grundlegende Konzeptgenerierung	L	x	■	■																
	2.2	Konzept-Entwicklung hydraulische offshore Energiespeicher Typ A	L		■	■	■	■														
	2.3	Konzept-Entwicklung hydraulische offshore Energiespeicher Typ B	L		■	■	■	■														
	2.4	Konzept-Entwicklung geeigneter Verankerungssysteme	L			■	■	■														
	2.5	Entwicklung und Analyse von Funktionsprinzipien zur zusätzlichen Energiespeicherung	L			■	■	■														
	2.6	Evaluierung und Auswahl der entwickelten Konzepte	L	x			■	■	■◆													
3		**Funktionalität und Simulation: Schwimmkörper**	L					↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔				
	3.1	Simulation und Analyse unter stationären Bedingungen	L					■	■	■	■	■	■	■	■	■						
	3.2	Simulation und Analyse unter dynamischer Stabilitätsbelastung	L					■	■	■	■	■	■	■	■	■						
	3.3	Ableitung von Konzepten zur Dämpfung der Rollbewegung	L											■	■	■	■	■				
	3.4	Simulation und Analyse von geeigneten Verankerungssystemen	L											■	■	■	■	■				
	3.5	Literaturstudium Materialien	L													■	■	■◆				
4		**Funktionalität und Simulation: Maschineneinheiten**		L				↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔		
	4.1	Literaturrecherche über maschinelle Lösungsansätze in der Pumpspeicherung		L				■	■													
	4.2	Variantenstudie		L						■	■	■										
	4.3	Variantenauswahl		L								■	■	■								
	4.4	Auslegung und Variantenvertiefung		L									■	■	■	■						
	4.5	3D-Cad Entwurf		L										■	■	■	■	■				
	4.6	Detailuntersuchungen und Simulation		L										■	■	■	■	■	■			
	4.7	Maßnahmenkonzept zur Nutzung eines korrosiven Fördermediums		L														■	■	■		
	4.8	Kostenschätzung		L															■	■◆		
5		**Studie: Kombinationsmöglichkeiten**	L															↔	↔	↔		
	5.1	Konzept-Entwicklung von Kombinationsmöglichkeiten mit Energieerzeugern	L															■	■	■		
	5.4	Konzept-Entwicklung von Kombinationsmöglichkeiten mit offshore Infrastruktur	L															■	■	■◆		
6		**Wissenschaftliche Evaluierung, Grundkonzeption für die weitere Forschung und Dissemination**	L	x	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔
	6.1	Wissenschaftliche Evaluierung	L	x																■	■	■
	6.2	Grundkonzeption für weitere F&E und Verwertung sowie Klärung von Schutzrechtsfragen (IPR)	L	x																	■	■
	6.3	Dissemination	L	x	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

UIBK……Universität Innsbruck
TUW…..Technische Universität Wien

L AP- bzw. Task-Leader
x Mitarbeit
◆ Meilenstein

Contact

Robert Klar
robert.klar@uibk.ac.at
office@buoyant-energy.com

Markus Aufleger
markus.aufleger@uibk.ac.at

Thank you for your attention!