Cleaning BC: The role of Wave Supplied Power in a Low-Carbon Energy System

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Professor, Department Mechanical Eng.
WCWI Director
29 February 2019
Following the maxim of the “5 Ws and the 1 H”

*I keep six honest serving-men
(They taught me all I knew);
Their names are *What* and *Why* and *When* and
*How* and *Where* and *Who*.*

Rudyard Kipling

*How the Elephant Got His Trunk*
Presentation Overview

Following the maxim of the “5 Ws and the 1 H”

Who am I?

What is wave energy?

What is a Wave Energy Converter (WEC)?

How is WEC technology development being supported?

Where will WECs be deployed in BC – and to what benefit?

How are researchers making WECs perform better?

Who will lead WEC development in BC / Canada?
**Who am I?**

* < 2003: cabled/towed ocean vehicles
  * cable dynamics, vehicle dynamics.

* 2003 – 2012: Remotely operated vehicle manipulators (ROVMs)
  * Articulated body dynamics, control, navigation.

* 2006 – 2010: SyncWave Energy Systems
  * Point absorber WEC dynamics, moorings

* 2012 – present: West Coast Wave Initiative
  * Wave resource assessment, WEC performance, community integration.

* 2017 – present: Co-director of PRIMED
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The West Coast Wave Initiative (WCWI)

**Goal**: Use field measurements and advanced numerical tools to define the benefits to be realized in BC through wave energy technology.
PRIMED: Pacific Regional Institute for Marine Energy Discovery

Commercialization Activities (Client Driven)

Tools, Methods & HQP

Academic R&D (Curiosity Driven)

SSDL Sustainable Systems Design Laboratory

University of Victoria Institute for Integrated Energy Systems

WCWI
Before we begin: WEC technology is NOT a new idea…

Attenuator (Pelamis)

“Anything one [person] can imagine other [people] can make real”

Jules Verne (1828-1905)

“Pelamis Wave Power Ltd is the manufacturer of a unique system to generate renewable electricity from ocean waves.”

http://www.pelamiswave.com/
WEC technology is NOT a new idea…

Attenuator (Pelamis?)
WEC technology is NOT a new idea…

Point Absorbers (OPT & WaveBob)

Frederick B. Marvin, US 1502511A1, 22 July 1924.

WEC technology is NOT a new idea…
What is an ocean wave?
Basic Wave Descriptors

Water waves are formed by oscillations of water particles beneath the sea surface. The descriptors that characterize a wave’s shape and behavior:

- **Wave Crest:** Highest vertical position of a wave
- **Wave Trough:** Lowest position of a wave
- **Wave Height:** Vertical distance from wave trough to crest (m)
- **Wave Period:** Time from one crest to the next crest (sec)
- **Wavelength:** Distance from one crest to the next crest (m)

Ocean waves only appear to transport mass

A water wave is formed by a out of phase elliptical orbits of water particles. The oscillations exist well below the sea surface (down to L/2). As particles are always accelerating – there is a oscillating pressure field.
Ocean waves to ocean swell

Wave Creation:
- Wind Speed
- Fetch (distance)
- Time

Ripples > Chop
Chop > Wind Waves
Wind Waves > Swell

Example:
Fetch: 50 NM (90 km)
Time: 6 Hours
Wind Speed...
To a stationary observer, wave crests propagate at a speed $C$ across the sea surface.

The propagation speed is related to the period, wavelength and the water depth – as waves propagate into shallow water they slow down.

Waves "feel" the bottom at a depth of approximately half of the wavelength. Since the seabed has an irregular profile, lower speeds develop in localized shallower regions.

When different speeds result across a crestline, the wave crests tend to "bend" towards shallower regions - this is known as refraction.

<table>
<thead>
<tr>
<th>d = water depth</th>
<th>Deep Water $d &gt; (L/2)$</th>
<th>Shallow Water $d &lt; (L/20)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave speed ($C$)</td>
<td>$C \sim 1.56 \frac{T}{T}$</td>
<td>$C \sim 3.13 \sqrt{d}$</td>
</tr>
</tbody>
</table>

In deep water
10 sec wave period $\Rightarrow C = 15.6\, m/s$

| Wavelength ($L$) | $L \sim 1.56 \frac{T^{1/2}}{T}$ | $L \sim 3.13 \sqrt{d}$ |

In deep water
10 sec wave period $\Rightarrow L = 156\, m$
Irregular waves & the Wave Spectra

Swell from storm # 1
Swell from storm # 2
Swell from storm # 3
Swell from storm # 4
Swell from storm # 5

Final sea surface

A Wave Spectrum

Wave Spectral Density

NOAA / NDBC

Frequency (Hz)

Power (m^2/Hz)
Directional wave spectra

A directional wave spectra
Wave statistics – average wave height and period

One Dimension Frequency – Energy Plot

$\textbf{Hs} =$ Significant wave height. Proportional to the area under the spectrum

$\textbf{Te} =$ Energy Period. Is the horizontal location of the center of spectrum area

$E(f) =$ Energy

$f =$ frequency

Peak frequency $f_p$

Mean frequency $\langle f \rangle$
Irregular waves – wave events

Individual Waves,
Significant Wave Height, $H_s$,
Maximum Individual Wave Height, $H_{\text{max}}$, and
Freak Wave

\[
\text{If } H_{\text{max}} > 2.2 H_s \rightarrow \text{freak wave event}
\]
What is wave energy?

Pressure creates force on a water particle moving with oscillating velocity.

Consider a screen door on line A-A’. There is a net ‘+’ rate of work done on the fluid across that gate over each wave period.
Wave energy: regular and irregular waves

\[ J = \frac{1}{32\pi} \rho g^2 H^2 T \]  \text{Watts meter}^{-1}

\[ J \approx \frac{1}{64\pi} \rho g^2 H_s^2 T_e \]  \text{Watts meter}^{-1}

Hs & Te relates to the “average” amplitude & period of the waves
Wave Energy

- Energy continuous oscillates between potential and kinetic states in a ocean wave.
- “Wave energy” refers to the average value of the total energy across one wavelength.
- “Wave energy transport” is a measure of the rate of energy delivery through an imaginary 1m wide “door”
## What is a Wave Energy Converter (WEC)?

<table>
<thead>
<tr>
<th>Type</th>
<th>Definition</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Attenuators</strong></td>
<td>• Aligned parallel to the direction of wave propagation.</td>
<td><img src="image" alt="Image of Attenuators" /></td>
</tr>
<tr>
<td>(Pelamis, Biopower)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Overtopping Devices</strong></td>
<td>• Top of breaking wave used to drive low-head turbine.</td>
<td><img src="image" alt="Image of Overtopping Devices" /></td>
</tr>
<tr>
<td>(Wave Dragon, Limpet, Manchester Bobber, OceanLinx, ORECON, SEEWEC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Point Absorbers</strong></td>
<td>• Omni-directional absorption – horizontal or vertical component of wave motion.</td>
<td><img src="image" alt="Image of Point Absorbers" /></td>
</tr>
<tr>
<td>(OPT, WaveBob, AOE Canada)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Terminators</strong></td>
<td>• Aligned perpendicular to the direction of wave propagation.</td>
<td><img src="image" alt="Image of Terminators" /></td>
</tr>
<tr>
<td>(AWS, OREC)</td>
<td></td>
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</tr>
</tbody>
</table>
**What is a Wave Energy Converter (WEC)?**

<table>
<thead>
<tr>
<th>Location</th>
<th>Nearshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore</td>
<td>Limpet WaveGen (UK)</td>
<td>SSG WAVEnergy (NO)</td>
</tr>
<tr>
<td>Nearshore</td>
<td>Oceanix Energetch (AU)</td>
<td>Waveplane (DK)</td>
</tr>
<tr>
<td>Offshore</td>
<td>OE Buoy Ocean energy (IRL)</td>
<td>Langlee LWP (NO)</td>
</tr>
<tr>
<td></td>
<td>CETO III REH (UK)</td>
<td>Oyster Aquamare (UK)</td>
</tr>
<tr>
<td></td>
<td>AWS Ocean (UK)</td>
<td>Wave Dragon (DK)</td>
</tr>
<tr>
<td></td>
<td>Pelamis PWP (UK)</td>
<td>PowerBuoy OPT (USA)</td>
</tr>
</tbody>
</table>

**Working Principle:**

- **OWC**
  - air-flux
  - movement: multiple structure
  - water-flux

- **Pressure Differential**
  - movement: single structure

- **Floating Structure**
  - movement: multiple structure

- **Overtopping**
  - water-flux

- **Oscillating Wave Surge / Impact**

---

**Terminator**

**Point absorber**

**Attenuator**
Wave Energy Converter (WEC) technologies

Oscillating Water Column (OWC)
Wave Energy Converter (WEC) technologies

Wave Overtopping

Wave Dragon in operation
Wave Energy Converter (WEC) technologies

Oscillating Flap
Wave Energy Converter (WEC) technologies

Attenuator (Pelamis)
Wave Energy Converter (WEC) technologies

Background: What is wave energy? | What is a WEC? | Where are WEC’s Developed?

Point Absorber (CETO 5 & 6 – Single Body Point Absorber, SBPA)

CETO 5 (240kW) to CETO 6 (1000kW)
Wave Energy Converter (WEC) technologies

Point Absorber (Ocean Power Tech. – Self Reacting Point Absorber, SRPA)
Who supports WEC development

WEC technology developers (purple) & dedicated infrastructure (red) (2016)
Who supports WEC development

European Programs

MARINET
FP7 funded initiative to share facilities across Europe
Standardize test methods
Coordinate test programs
Outreach and education (short courses)

FP7: EU 7th Framework Programme for Research
Who supports WEC development

Background: What is wave energy? | What is a WEC? | Where are WEC’s Developed?

European Programs

MARINET

WaveStar (Denmark) partnered extensively with Aalborg University.

- Wave structure interactions
- PTO control
- Tank tests – physical modeling of power take-offs
European Programs

DTOcean

European Union's Horizon 2020 Fund

Develop computational tools for WEC design and assessment.

€ 8M program run between 2018-2021.

20 partners (academia, NGO, industry).
International WEC Test Sites

Cornwall Wave Hub
International WEC Test Sites

Wave Energy Test Site (WETS) at Kaneohe Bay, HA
Pacific Marine Energy Center
South Energy Test Site

- Wave devices under test
- Research vessel
- Sub sea pod
- Anchoring infrastructure not shown
- Research device
- Devices will be 6 nautical miles from shore (0.9 miles)
- Cables bring power to shore and connect to utilities
- Buried cable back to shore

NETS
North Energy Test Site
2 Nautical Miles From Shore

SETS
South Energy Test Site
5 Nautical Miles From Shore

Universities and organizations involved:
- University of Victoria
- Institute for Integrated Energy Systems
- U.S. Department of Energy
- Oregon State University
- PMEC
- NNfREC
- PMEC
- WCWl
Marine Energy at OSU

- Early 2000s: Initial research in wave energy
- Mid 2000s: IP licensed by Columbia Power; OSU-CPwr team develop wave energy converter
- 2008: NNMREC consortium established at OSU and University of Washington through DoE grant; OSU and CPwr test wave energy converter in Newport, Oregon
- 2012: DOE requests NNMREC to accelerate development of grid-connected, multi-berth, open-water test site, PMEC-SETS
- 2014: University of Alaska Fairbanks joins NNMREC
- 2017: NNMREC awarded $35M to develop PMEC-SETS
- 2017: NNMREC rebranded to PMEC, PMEC-SETS rebranded to PacWave

External Funding (since 2009): ~$108M to PMEC R&D and affiliated testing; ~$66M to OSU
PMEC and PacWave activities are supported by the US DOE and the Oregon Wave Energy Trust (OWET).

**US DOE – Water Power Program**

- Wave energy benefits from being inside the WPP (grouped with hydroelectricity)
- Wave Energy Prize – $2.25M competition to encourage new WEC designs.

**OWET**

- Funded through state lotteries.
- Provided $6M between 2008-2013 to academics and industry projects.
Canada – funding WEC development

Pre-2012 Canadian WEC funding used a “technology push” model.
Syncwave Energy Systems (2008-2010) is a good case study (I think the only case study)

Sustainable Development Technology Canada – $2.7M
BC Innovative Clean Energy Fund - $2.0M
NRCan Clean Energy Fund – $4.6M

None of these funds were ever accessed as the matching private equity could never be raised.

Investors were faced with too much uncertainty in the target market, what COE could be achieved, what COE needed to be achieved...

Since 2012, Canadian gov investment in WEC R&D has been limited to the WCWI and PRIMED.
Why is the WCWI necessary?

WCWI: Why is it needed? | What are the objectives? | How? | Who?

WEC demonstration deployments are necessary, but not sufficient

WaveBob (Ireland):
- Selected for deployment on the Cornwall Wave Hub.
- “Innovation Company of the Year” – Engineers Ireland, 2006.

WaveBob Shuts Down After Failing to Raise Funds, Find Partner
(Bloomberg.com, 3 April 2013)

“Some of the big players in ocean energy are in fact withdrawing from the sector entirely... Finding a strategic partner and a long-term investor has been impossible and we were almost there a couple of times but they haven’t materialized.”
By looking into the future, integration studies allow for scenario based analyses in which:

- “Know-how” evolves (WEC control).
- Priorities change ($ value of GHG reductions).
- Sensitivity of levelized cost of energy (LCOE) to these changes can be determined (62 ¢/kWh, 50 ¢/kWh, 15 ¢/kWh, …).

Detailed WEC integration studies are a necessary complement to WEC demonstrations.

A WEC demonstration is limited to demonstrating present day know-how.

Why is the WCWI necessary?
Why is the WCWI necessary?

Australia’s ‘OceanLynx’, formerly ‘Energetech’ (March 2014)
WECs in BC – we almost bought an Ocean Lynx unit…

2000 IEP: The trend in deterioration of the HVDC terminal station equipment confirms that both HVDC Pole 1 and Pole 2 are expected to retire in stages by the year 2007….New supply for Vancouver Island will be required in 2007.

*From the 2004 BC Hydro IEP
WECs in BC – we almost bought an Ocean Lynx unit...

Vancouver Island 20 MW Green Energy
4 MW Wave Energy (1st Phase of Development)

Select JV
Interim CAR
Identify partners
RFP
Evaluate bids
Negotiate
Finalize

Monitor
Monitoring
Extra Monitoring
Analyze data
Prelim design

Design
Decision making
Financing
Design

Build
Engineering
Procurement
(EPC)

Generate

6 months
8 months
4 months
6 months
20 years

01 Nov 2001
01 July 2002
01 Nov 2002
01 May 2003
What is the West Coast Wave Initiative (WCWI)?

The WCWI is a comprehensive wave-to-wire-to-washing machine modeling study that includes:

• Detailed assessment of the wave energy resource in an important Canadian region – Vancouver Island.

• High fidelity time domain computer simulations of Wave Energy Conversion (WEC) technologies.

• Detailed integration studies that examine how wave energy should be used at kW, MW and GW scales.
WCWI – early stage WEC performance assessment

WCWI – BC Coast SWAN Model

SWAN Model Grid (V3):
- 190,000 square km’s
- 90,000 grid points
- ~50m nearshore spatial resolution
Field Monitoring

Estevan: (Mid-island)
• Winds, Waves, Currents
• 3 years @ hourly resolution

Amphitrite: (Ucluelet)
• Winds, Waves, Currents
• 5 years @ hourly resolution

Florencia Bay: (Ucluelet)
• Waves
• ~25m deep & 500m offshore
• 2.5 yrs @ 20 min resolution
• Carnegie Investigative Use Permit

Port Renfrew:
• Waves and Currents
• ~25m deep (shallow)
• 1 yr @ 20 min resolution

Port Hardy:
• Waves and Currents
• ~ 40m deep (shallow)
• Collocated buoy & AWAC
Where will WECs be Deployed (in BC)?

Wave energy (kW/m) > 90th percentile regions

<table>
<thead>
<tr>
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<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Energy Flux [kW/m]</td>
<td>Area [km²]</td>
<td>Energy Flux [kW/m]</td>
</tr>
<tr>
<td>Raw</td>
<td>37.05</td>
<td>1040</td>
<td>36.67</td>
</tr>
<tr>
<td>Fre Filtered</td>
<td>19.83</td>
<td>1145</td>
<td>19.59</td>
</tr>
<tr>
<td>Fre-dir Filtered</td>
<td>14.15</td>
<td>1098</td>
<td>14.38</td>
</tr>
</tbody>
</table>

“Strategic”

“Good from the perspective of all stakeholders”

Legend

- Raw Wave Resource
- Frequency Filtered Wave Resource
- Frequency-directional Filtered Wave Resource

Economic Value Of Commercial Fishing

University of Victoria | Institute for Integrated Energy Systems
Where will WECs be Deployed (in BC)?
WCWI: Why is it needed? | What are the objectives? | How? | Who?

<table>
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<th>Energy Type</th>
<th>Value</th>
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<tr>
<td>Annual Gross Energy</td>
<td>28,704 GWh</td>
</tr>
<tr>
<td>Annual Extractable Energy</td>
<td>11,696 GWh</td>
</tr>
<tr>
<td>Van Isle Electricity Demand</td>
<td>9,069 GWh</td>
</tr>
</tbody>
</table>

Legend

Energy Flux [kW/m]
- 12.37 - 13.67
- 13.68 - 13.89
- 13.9 - 14.11
- 14.12 - 14.3
- 14.31 - 14.47
- 14.48 - 14.62
- 14.63 - 14.82
- 14.83 - 15.11
- 15.12 - 15.6
- 15.61 - 18.6
Wave energy – it’s good to have constraints

Ocean Energy Systems (OES) of the International Energy Agency (IEA) estimates that the global wave resource potential could be 29,500 TWh/year.
Wave energy – it's good to have constraints
Wave Resource Histogram

WEC Performance Matrix

Annual Energy Production Profile

Annual Energy Production (AEP)
Annual Energy Production (AEP)

Fig. 7. WEC mean power output during January 2014
How do simulations enable design optimization

Point Absorbers and the ‘other’ Valley of Death

- Point absorbers suffer from a parasitic roll motion that develops (usually) right at the frequency of peak power conversion.
A point absorber ‘walking’
Using moorings as a design feature of the WEC
Using moorings as a design feature of the WEC
Using moorings as a design feature of the WEC
Hot Springs Cove is a community of the Hesquiaht First Nation. Currently pursuing a combination of renewables to eliminate diesel fueled energy generation on site.
Hot Springs Cove – energy demand

WCWI: Why is it needed? | What are the objectives? | How? | Who?

Hot Springs Cove is a community of the Hesquiaht First Nation. Currently pursuing a combination of renewables to eliminate diesel fueled energy generation on site.
Considered a ‘SurfPower’ point absorber
Device power in all sea states scales linearly with length (distance into page)
Used ProteusDS to generate a performance matrix
Capped device output at 100kW
Figure 2.24: SurfPower specific performance matrix
Hot Springs Cove – break even analysis

We consider all renewables to be added at zero cost – we want to assess savings over the Business as Usual (BAU) case over lifetime of project.

Converting those savings into present day value gives us a measure of a (CAPEX+OPEX) allowance for the renewable device.

Demand side: peak shifting (delaying loads to reduce peak demand)
Hot Springs Cove – Avoided costs

- **DIESEL**: $34,889,808
- **HYDRO**: $15,943,942
- **WAVE STORAGE**: $10,516,794

Break-Even Cost:
- Avoided Cost: $827,289
- Avoided Cost: $4,699,371

Avoided Cost: $18,955,865
Hot Springs Cove – LCOE

**Diesel system**

\[ 1.519 \text{ \$/kWh} \]

*Includes an overhaul*

**Hydro system**

\[ 0.6995 \text{ \$/kWh} \]

**Wave system**

\[ 0.6534 \text{ \$/kWh} \]

**Optimized system**

\[ 0.4545 \text{ \$/kWh} \]
Results illustrate the synergy of wave supplied power with a winter heating dominated community demand profile.

Wave resource is somewhat correlated with hydro but persists more in the summer – this leads to further decreases in system LCOE.

Load shifting and battery storage (200kWh) didn’t show much benefit with hydro or wave.

At HSC – hydro is now being built to form a Micro-Hydro Diesel system (MHD)

Can we provide some guidance to HSC on how to continue to evolve their energy system after the MHD step?

• wave vs. solar.
• Battery storage – 200kWh, 500kWh, ...?
• Energy Saving – new insulation, windows, ... (ES)
Hot Springs Cove – planning renewable buildout

MHD + 100 kW Wave + No BSS

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>BAU</td>
<td>15.94</td>
<td>85,305</td>
<td>227</td>
</tr>
<tr>
<td>Wave</td>
<td>11.21</td>
<td>44,664</td>
<td>119</td>
</tr>
<tr>
<td>Δ</td>
<td>- 29%</td>
<td>- 48%</td>
<td>- 48%</td>
</tr>
</tbody>
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Allowable Cost =$M 4.70

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>100 kW diesel</td>
<td>0.074 (0.096)</td>
<td>0.203 (0.417)</td>
</tr>
<tr>
<td>250 kW diesel</td>
<td>0.000 (0.052)</td>
<td>&lt;0.001 (0.018)</td>
</tr>
</tbody>
</table>
Hot Springs Cove – wave pathway

By examining the differences in NPOC, emissions and fuel consumption between cases we can create pathways of incremental improvements.

Figure 4.7: Expected incremental diesel displacements [L/yr] due to traversing the wave (100 kW) tech tree
Hot Springs Cove – WEC costs

Commercial Potential of Marine Renewables in British Columbia, Natural Resources Canada, 2019

Surveyed:
• WEC CAPEX costs (30,000 $/kW)
• expected learning rates (12%)
• Capacity Factors (~28%)

Established projection for WEC LCOE reductions over time.

At HSC the 100kW WEC plant can have an allowance of $4.7M. It produces 496 MWh/yr
• Allowable LCOE = 379 $/MWh
Hot Springs Cove – energy balance & incremental costs

WCWI: Why is it needed? | What are the objectives? | How? | Who?

Projected LCOE ($/MWh) of MRE vs diesel-generation and IPP cost

Small scale WEC

- Tidal - commercial
- Tidal - community
- Wave - commercial
- Wave - community
- IPP cost
- Diesel-generated cost
- RHE - community
CleanBC & remote communities

- Majority of BC’s off grid energy systems are in First Nations communities.
- BC First Nations have made it very clear that cleaning their energy systems is a priority.
  - 78 projects with over 1.8 GW of installed capacity (60% micro-hydro).
  - 48 projects in planning or pre-planning.
  - 250 projects in early stage feasibility.
- A majority of existing projects (42) are grid connected, but recent projects are off-grid.
- Clean energy systems are a means to shape (re-shape) communities consistent with traditional ideals of people and place.
There still remains a lot of uncertainty in WEC technology

- Concepts haven’t converged.
- CAPEX & OPEX.

Advancement of the sector depends on motivated people who want to pursue transformational change.

In BC, it is Indigenous communities that are taking the lead.

IEA – OES:

“Ocean Energy is facing a dilemma: how to fund technological development and first deployments at sea oriented to gain experience, improve performance, limit risks and finally reduce costs in a challenging long-term scenario. The participation of public bodies committed to a clean energy future using indigenous sources is essential to help solve this dilemma. It can bridge the gap between a promising present and a profitable future”.
How many litres of diesel do we need to displace in order to fill the 6.1Mt missing piece?

\[ 2.3 \times 10^9 \text{ L} \]

There are 3000 off grid communities in Chile...