2.5 Tidal power plants (TPP)

[Won-Oh Song, W. van Walsum]

2.5.1 Introduction

This section is intended to give an understanding to the reader of where tidal power technology stands in the year 2000, where it may have potential applications and how these applications might be quickly assessed. It was assumed that the reader has a specific tidal coastal zone in mind and is looking for an answer to the question: “What is the tidal energy potential of this particular site and in which ways can that potential be developed.”

Since the mid-nineteenth century, hundreds of patents dealing with the extraction of tidal energy have been registered. The greatest number of such inventions deals with the extraction of tidal energy from a well-defined body of tidal water such as floats of a given size being moved up and down by the tides. In such an application, the size of the float and the tidal range will define the oscillating body of water, the movement of which defines the theoretical maximum amount of energy that might be generated and which is referred to as the float’s *natural energy*. To get any appreciable amount of natural energy out of such devices, the floats or other devices as the case may be, would have to be excessively large [97Ber]. For this reason, this section has been confined to Tidal Power Plants which extract *potential* energy from water stored in tidal *basins*. In this case, the amount of natural energy available is that as defined by the size of the basin and the tidal range. When looking at floats, a float of 1000 m^2 in surface area may be considered large. A basin of 1 km^2 would be considered small. The extraction of energy from tidal basins brings us to installations of a few MW all the way up to a few thousand MW. Plants in the order of a few MW could play a role in community-self-sufficiency programs. The larger plants would deliver their energy to the surrounding utility systems or industries.

The general trend in this 21st century is to favor the small over the big, a sentiment generally expressed by the slogan “Small is beautiful”. A reader looking into this section with the “small is beautiful” mind-set would quite likely be or represent a self-sufficiency advocate. That reader would also look at solar energy to heat a home or water, he would look at the possibility of a windmill to provide electrical power, and being located near tidal waters, he wants to find out what tidal power might do for him to achieve his self-sufficiency goal. This type of reader is advised to study Sect. 2.7 and consider extracting kinetic energy from tidal currents, using horizontal-axis propeller turbines or vertical axis “Darrieus” turbines or variations thereof such as the “Helical” turbine.

Between the mid-sixties and mid-eighties, several experimental and pilot TPPs which extract energy from tidal basins have come on stream as discussed under Sect. 2.5.6. Little has happened during the last fifteen years in the way of designing and building state-of-the-art tidal power plants. Construction in the ocean environment however has developed over the last forty years by leaps and bounds. Also in the field of hydro power generation, new developments have occurred such as variable speed turbine-generators and control of a plant through power-electronics rather than mechanical means. These technologies are all in a stage of maturity and are applicable to TPPs. Readers interested in the way opinions concerning the design, construction and operation of TPPs have developed over the years might refer to [65Ber], [66Gib], [91Bak] and [97Ber].

All through this section, the international standard SI units are used together with a few non SI units, recognized by the Comité International des Poids et Mesures as having practical importance in certain fields; thus the time t is not only measured in the official SI unit of seconds [s], but also in minutes [min] and hours [h]. Table 2.5.1 gives an overview of the symbols as used in this section with their units of measurement.

Table 2.5.1. Definition of symbols as used herein with their units of measurement.

Definition of elements	Symbol	Unit	Notes
Tidal range	R	m	
Mean tidal range	R_{mean}	m	
Maximum tidal range	R_{max}	m	
Root-mean-square range	R_{rms}	m	Root of the mean value of the square of tidal ranges
Surface area	A	m^2	Always a site-specific function of L, expressed in km^2 when so noted.
Surface area tidal basin	A_b	m^2	
Surface area high basin	A_h	m^2	
Surface area low basin	A_l	m^2	
Max. area high basin	$A_{h\,max}$	m^2	
Area high basin at El. *r*	$A_{h\,(r)}$	m^2	
Water level	L	m	Above datum
Water level sea	L_s	m	Above datum
Water level basin	L_b	m	Above datum
Water level high basin	L_h	m	Above datum
Water level low basin	L_l	m	Above datum
Head	H	m	Difference in water levels across sluice or turbine
Turbine's rated head	H_{rated}	m	
Flow of water	Q	m^3/s	
Flow sea to high basin	Q_{sh}	m^3/s	
Flow high to low basin	Q_{hl}	m^3/s	
Flow low basin to sea	Q_{ls}	m^3/s	
Flow high basin to sea	Q_{hs}	m^3/s	
Turbine's rated discharge	Q_{rated}	m^3/s	
Discharge coefficient	C_D	-	Used for both sluices and turbines
Time	t	s	
Duration of tidal cycle	t_s	s	$t_s = 44700$ s
Throat area of openings	F	m^2	
Density of sea water	ρ	kg/m^3	1040 kg/m^3
Power	P	kW	Also in MW and GW
Rated power	P_{rated}	kW	Generator's limiting capacity
Volume	V	m^3	
Turbine/Gen. efficiency	T_e	%	
Elevation	El	m	Above datum
Highest high water level	*HHW*	m	Above datum at mean equinoctial tide
Mean water level	*MWL*	m	Above datum
Mean high water	*MHW*	m	Above datum
Mean low water	*MLW*	m	Above datum

2.5.2 The tides

2.5.2.1 Cause and effect

The tides around the earth are produced by extremely small variations in the gravitational forces, primarily those of the earth itself, its moon and the sun. These small variations in the gravitational forces acting on very large masses of water result in tides at mid oceans with a typical range in the order of 30 cm. On Lake Superior, the tidal range is of the order of 5 cm. In the Mediterranean Sea, the tides are similarly negligible. For an historical treatise of man's perception of the tides see [99Car].

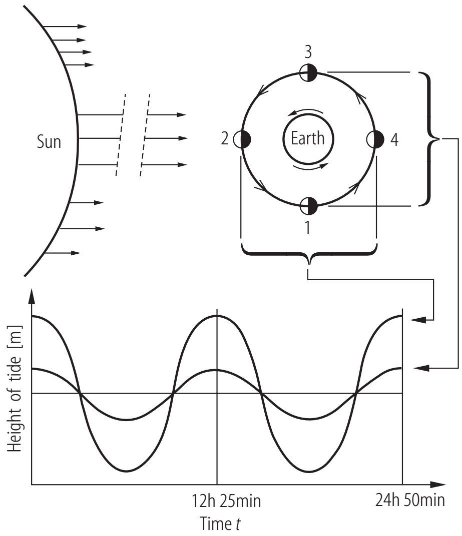

Fig. 2.5.1. Top: Interaction between Sun, Earth and Moon. The moon rotates around the earth in a 29½ day cycle: 1 - first quarter; 2 - new moon; 3 - third quarter; 4 - full moon.
Bottom: The tidal cycle, Height of tide vs. time. Two high tides and two low tides occur in every moon day of 24 hours and 50 minutes. Spring tides generally occur shortly after new moon and full moon; neap tides shortly after first quarter and third quarter.

2.5.2.2 Characteristics

As the moon rotates around the earth, the ocean's high tides move with it from east to west. In general, tides of exceptional amplitude occur shortly after a full moon or a new moon (“spring tides”) and shortly after a first and a last quarter (“neap tides”), see Fig. 2.5.1. Along most of the coast lines around the globe, the tides are thus in tune with the movements of the moon. In the Bay of Fundy for instance, every 24 h 50 min, i.e. a *moon day*, there are two high tides and two low tides, with spring tides after new- and full-moon and neap tides after first- and last-quarter, similar to what happens at Mont Saint Michel in the Gulf of St. Malo, France and numerous other locations. These are regular, semi-diurnal tides. This is not the case however along all the earth's coastal waters. For instance, at Do Son on the Gulf of Tonkin (Vietnam), there is only one high tide and one low tide every moon day. In Tahiti, high and low tides occur at the same hour every day. They are in tune with the sun. For a preliminary assessment of the tidal power potential of a specific site, tide tables as published by various government agencies provide practical and reliable information.

When preparing the final design for a tidal power plant, combinations of astronomically produced extreme tides, both low and high, should be considered in combination with extreme meteorological events [78Woo].

2.5.2.3 Resonance

That ocean tides with a typical range of 30 cm can cause tidal oscillations at the head of some ocean inlets of up to an average range of 12 m is explained by resonance. When the ocean’s regular tidal rhythm of one push and one pull every 12 h and 25 m is in harmony with an embayment’s natural frequency of oscillation, resonance will occur. In this way, large masses of coastal waters are constantly kept in a spectacular oscillating mode. If a dam were to be constructed to cut such a bay off from the ocean, then there would be no exciting forces acting on the waters of the bay and as a result, there would be no resonance. Tidal dams therefore are capable of killing the goose which was expected to lay the golden eggs. Any major tidal dam project therefore has to include an analysis of what a dam might do to the natural frequency of oscillation of the tidal basin involved. This simple view of relating amplitude directly to the period of the system is not always born out upon closer scrutiny. Besides the change in the period of the system, there are two other important processes to be considered. First of all, a barrier can change the shape of the basin and secondly it may affect the energy dissipation processes in various parts of the bay. Both these factors mean that predictions of the tidal amplitude on the basis of change in period alone cannot readily be made. Mathematical studies of tidal behavior in response to the construction of tidal barriers must be an integral part of any major tidal power project. This type of studies has become a specialty within the oceanographic scientific community. A pioneer in this field is Prof. N.S. Heaps, who was associated with the Institute of Oceanographic Sciences in the U.K. [90Gre], [82Hea], [79Owe], [78Fon], [74Hea], [72Hea].

2.5.2.4 Energy potential

Robert Gibrat, Consulting Engineer to Electricité de France on tidal power issues, refers in [66Gib] to the expression *natural energy* which is a useful concept in assessing the tidal energy potential of a tidal basin. Let us consider a tidal basin, defined by

- tidal range R [m] and
- surface area basin A_b [m^2],

which is a function of the water level r in the basin, hence $A_b(r)$. The basin is separated from the sea by a barrage equipped with an infinite number of 100% efficient, double effect turbine-generators, meaning that the machines can generate electrical energy on both the incoming and the outgoing tide. The maximum amount of energy that could theoretically be extracted during one tidal cycle from this basin would be obtained by letting the basin instantaneously fill up through its 100% efficient turbines, from its lowest possible level to its highest level at the moment the ocean tide is at its highest. The water in the basin would then be kept at this highest level and again instantaneously released through the turbines from basin to sea at the moment the sea level is at its lowest. This theoretical maximum amount of energy which can be extracted during one tidal cycle is referred to as the one tidal cycle natural energy of that basin.

For a 100% efficient hydro plant, the energy E in [J] supplied by a water volume V falling over a height of h meters is

$$E = \rho\, g\, V\, h. \tag{2.5.1}$$

The power output P in [W] of such a plant is then

$$P = \rho\, g\, Q\, h. \tag{2.5.2}$$

The energy $E_{\text{tidal cycle}}$ in [Wh] generated by filling and emptying a tidal basin in this manner through one tidal cycle thus becomes

$$E_{\text{tidal cycle}} = \rho\, g\, V\, R\, /3600, \tag{2.5.3}$$

with V in [m^3] the volume of the tidal basin over the tidal range R in [m], see Fig. 2.5.2.

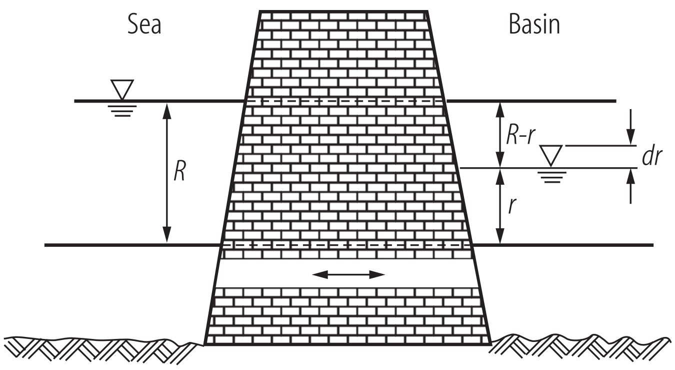

Fig. 2.5.2. Calculating the natural energy potential of a tidal basin with tidal range R, r being the height of the water in the basin above sea level.

To obtain the natural energy potential of a tidal basin for a year's duration, the annual tide histogram of that basin must be considered. Since the energy potential of a basin is proportional to the square of its tidal range, one can use the root-mean-square value of the tidal ranges over a year's duration, R_{rms}, to calculate $E_{nat/year}$ in [Wh]. The total number of tidal cycles per year is 705.5. Thus the amount of natural energy, dissipated per year in one tidal basin is

$$E_{nat/year} = 705.5\, \rho\, g\, V R_{rms}/3600, \quad (2.5.4)$$

with V the volume of the tidal basin in [m^3] over the tidal range R_{rms} in [m]. By substituting the known values for ρ and g into (2.5.4), we obtain

$$E_{nat/year} \approx 2000\, V R_{rms} \qquad \text{(unit: Wh)}. \quad (2.5.5)$$

To further simplify the procedure for estimating $E_{nat/year}$ for a tidal basin, Gibrat suggests [66Gib, p. 182]

$$E_{nat/year} \approx 0.7\, A\, R^2 \qquad \text{(unit: GWh)}, \quad (2.5.6)$$

where $A = A_{HHW}$ in [km^2] and $R = R_{max}$ in [m]. This provides indeed a simplification since R_{max} is often directly available from the tide tables, and A_{HHW} can be readily measured from hydrographic charts. The simplified method is useful in making a preliminary, comparative assessment of the tidal power potential for a number of basins being considered for tidal power development. Once only a few sites remain in such a preliminary assessment it would be of interest to compare the energy potentials of those few sites on the basis of formula (2.5.6).

What percentage of a basin's natural tidal energy potential can be realized depends on a number of factors which will be discussed in Sect. 2.5.4.

2.5.2.5 Coastal zones with substantial tides

Any site with a tidal power potential being proportional to the square of the tidal range are the places with substantial tides where tidal power riches may be found. The two references [97Ber] and [91Bak] give glimpses of the numerous TPP sites which have been identified and studied during the last several years.

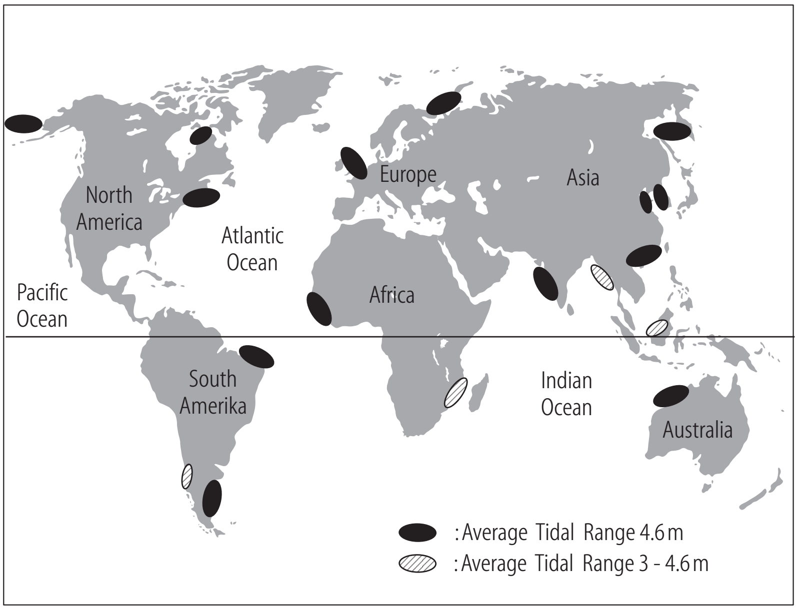

Fig. 2.5.3. Sites around the world with potential for tidal power development.

2.5.3 Schemes and operating modes of TPPs

Much ingenuity has been invested in finding effective ways of extracting energy from tidal basins, resulting in a large number of highly imaginative schemes. Practical engineering considerations and environmental concerns have reduced the number of viable options to four:

(a) *Single-basin, double effect plant*
The simplest tidal power plant consists of a basin, separated from the sea by a barrage, part of which would be a powerhouse equipped with hydraulic turbines. Water would enter and leave the basin through the turbines, generating energy on both the incoming and outgoing tides. Such turbines are referred to as *double effect* turbines. In addition, sluices could be provided in the barrage to raise or lower the water level in the basin to maximize the energy production.

(b) *Single, high-basin plant*
A single basin plant, equipped with sluices and single-effect hydraulic turbines, will be referred to as a single, high-basin plant if the sluices, together with the turbines in the sluicing mode, are used to fill the basin to its highest possible level at high tide and the water is released through the turbines at low tide, generating power under the maximum possible head.

(c) *Single, low-basin plant*
By the same token, sluices and single-effect turbines can be used to lower the water level in the basin at low tide to its lowest possible level and generate energy at high tide by turbining from sea to basin. Such a plant will be referred to as a single, low-basin plant.

The output of the above three types of plants can be augmented by pumping water near slack tide against a low head in one direction and releasing the same amount of water under a higher head in the opposite direction. Such pumping operations would be performed by the turbine-generators working in reverse as pump-motors.

Technically it may be quite feasible to operate one and the same plant, if fitted with double-effect machines, in all three of the above listed modes of operation, switching from one mode to another in response to the electric power market's demands. The La Rance plant for instance, as described in Sect. 2.5.6.1, has the flexibility such a varied operation requires. However, experience with operating the La Rance plant has shown that, from an environmental point of view, *regularity* in operating a tidal power plant is of utmost importance. Since environmental considerations do carry much weight, it has been assumed in this section that single-basin tidal power plants of the future will be designed for and operated in only one of these three modes.

The energy production patterns for each of the above three types of single-basin plants are shown in Fig. 2.5.4a, b and c. The observant reader will notice that, in drafting Fig. 2.5.4a, it was assumed that the tidal power plant in question was equipped with sluices. It should be noted that sluices are *not* an essential part of a single basin, double effect tidal power plant.

In comparing the above three types of tidal power plants, it is clear that a plant of type (a) produces *four* blocks of energy per moon day while plants of types (b) and (c) produce only *two* such blocks in the same time frame. This indicates that the energy produced by a plant of type (a) would in general be easier to absorb in an electric utility system than the energy produced by either one of plants (b) or (c).

When comparing the plant types (a), (b) and (c) on the basis of the amount of energy produced at a few potential TPP sites in the Bay of Fundy, it was found that a plant of type (c) produces the least. A plant of type (b) is superior to one of type (a) in a tidal regime in which the mean tidal range R_{mean} is less than 9 to 10 m while a plant of type (a) is superior in larger tidal ranges.

Why then would one bother with plants of type (c)? Such a plant should be considered in case a single high-basin plant is in operation and the construction of an additional plant is being considered. Having a plant producing energy on the outgoing tide, it would from an energy absorption point of view make sense to build the next plant to produce energy on the incoming tide. Such a combination of two independently operating but yet complementary single-basin schemes will be referred to as a *paired-basins* scheme.

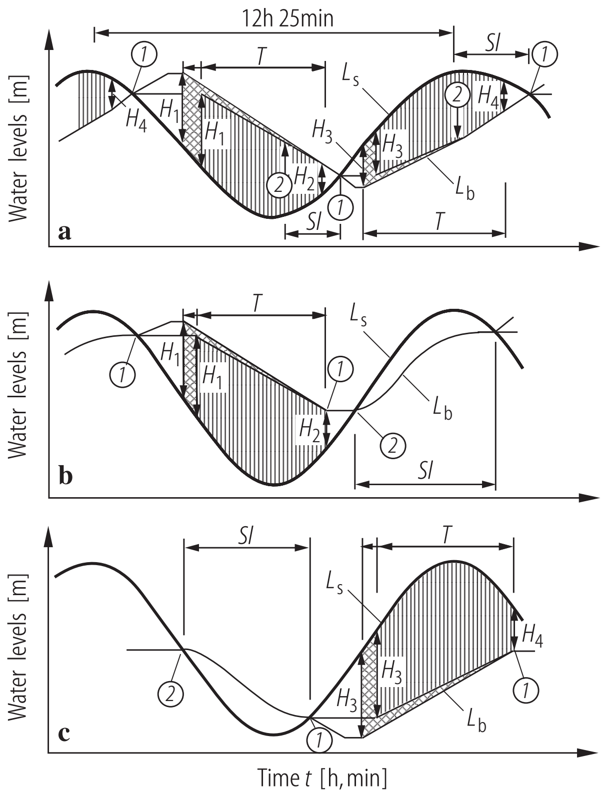

Fig. 2.5.4. Operating modes for single basin tidal power plants, showing water elevations of sea and basin vs. time. **(a)** single basin, double effect plant, generating energy on both incoming and outgoing tides. **(b)** single high-basin plant, generating energy on outgoing tide only. **(c)** single, low-basin plant, generating energy on incoming tide only. Legend: L_s - water level on sea-side of barrage; L_b - water level in tidal basin; *T* - turbining; *Sl* - sluicing; H_1 - start-up head for direct turbining; H_2 - stopping head for direct turbining; H_3 - start-up head for reverse turbining; H_4 - stopping head for reverse turbining ("direct" turbining means basin-to-sea, "reverse" sea-to-basin); *(1)*: start of either idle or pumping period (In case of idle period, basin level stays constant until power generation or sluicing starts. In case of pumping into basin, basin level rises until pumping stops. In case of pumping out of basin, basin level goes down until pumping stops); *(2)*: start of sluicing. Vertical-hatching indicates "true" tidal energy, cross-hatching "extra" energy thanks to pumping. Note that turbining periods start sooner when pumping is employed (Energy required for pumping not shown).

Over the years, the problem of getting energy on demand out of a tidal power plant has been intensely studied. Many of the hundreds of patented inventions deal with the challenge of making the tides provide power on demand. All such efforts have so far resulted in reduced output at an inflated cost per kWh of energy produced. Consider for example the ingenious *Caquot-Defour cycle* as described with thirteen other schemes in [97Ber]. Here, we are entering the realm of multi-basin tidal power schemes. For an understanding of the Caquot-Defour cycle, refer to Fig. 2.5.5. As shown in plan view, this scheme requires a high basin, a low basin, a middle basin and a powerhouse which would generate energy by flow through the turbines from left to right. At the upstream side of the powerhouse, Caquot-Defour calls for a fore-bay which is connected by sluice gates to the middle basin, the upper basin and the sea. At the downstream side of the powerhouse, an after-bay is called for which, by means of sluice gates, is connected to the middle basin, the low basin and the sea. The dams separating the high and the low basins from the sea would also be fitted with sluice gates by means of which the water levels in these two basins would be kept as high and as low as possible, respectively. See also [84Bou, p. 599-601]. It must be realized that water passing through a sluice causes energy loss due to friction and turbulence, but more relevant is the fact that, irrespective of a sluice's hydraulic efficiency, a head across the sluice is required to force the water through. It can readily be shown that for several of the operating cycles shown, the head loss due to those entire sluice passages would amount to at least 45% of the total available head. Thus at great expense the Caquot-Defour cycle loses 45% of the available energy and achieves a daily generation pattern which provides continuous but not uniform output. The large inequalities between neap and spring tides still exist.

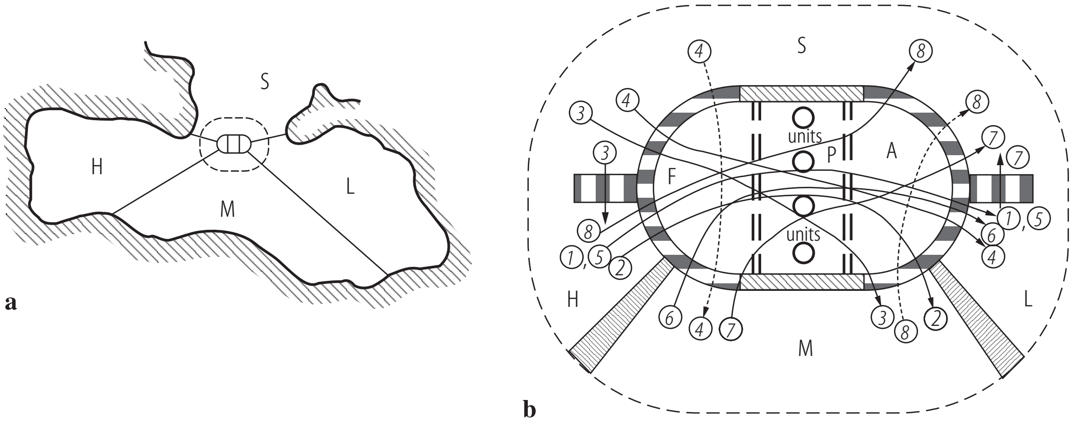

Fig. 2.5.5. Three-basin TPP to be operated according to the Caquot-Defour cycle. S - sea; H - high basin; M - middle basin; L- low basin; F - fore-bay; P - powerhouse; A - after-bay. In **(b),** the curved lines with numbers portray the various operating modes which would follow each other in the sequence of those numbers [97Ber, p. 34].

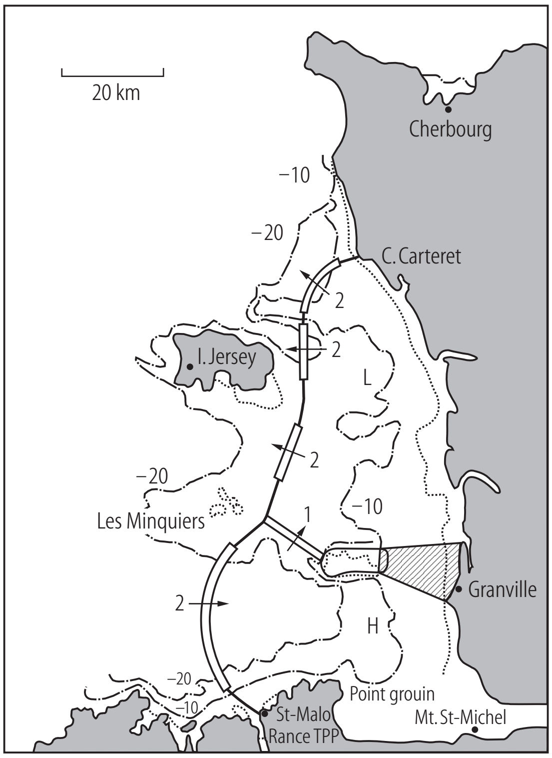

Fig. 2.5.6. Schematic arrangement of a double-basin TPP as proposed by Caquot, EDF [97Ber, p. 287]. Legend: H - High basin; L - Low basin; 1 - power house; 2 - sluices for filling the high- and emptying the low basin.

From various tidal power schemes, studied in France, the U.K., the USA, Russia and Canada, a consensus has developed to the effect that a single basin scheme is most suitable for extracting the maximum amount of energy out of a given site at the lowest unit cost. Double or multiple basin schemes were believed capable of producing a certain amount of firm capacity plus fuel-displacement-energy but at a unit energy cost which was much too high. The single basin schemes therefore appear to be favored in tidal power circles as of the start of the 21st century. ([97Ber, p. 287, 293], [93Cla, p. 2653], [91Bak, p. 33]). However, none of the double basin schemes considered was to be designed and operated *to yield energy at the lowest possible unit cost*. As soon as the words "double basin" were mentioned it was accepted as axiomatic that such plants were only conceived for one reason, i.e. to provide a constant output of power. It was Mr. George C. Baker, the driving force behind the design and construction of the Annapolis tidal power plant in Nova Scotia, Canada, who at one time suggested that linked-basins schemes might perhaps be proven efficient energy producers if provided with *large sluicing capacities.* It was subsequently established that linked-basins schemes, in a favorable geographic setting, can indeed be designed to produce tidal energy at the lowest possible unit price and in four blocks of energy per day rather than two. This means that for future tidal power studies, a fourth scheme should be kept in mind:

(d) *Linked-basins plant*
Such a plant consists of two basins, one high and one low with a single-effect power plant in between generating energy from the high to the low basin. The dikes separating the basins from the sea would have sluice gates for filling the high and emptying the low basin. The energy production pattern for such a plant is shown in Fig. 2.5.8.

With a linked-basins plant, water will pass from sea through sluices to the high-basin, from the high-basin through the turbines to the low-basin and from the low-basin through sluices to the sea. With two passages through sluices, it is important to have an ample and efficient sluice capacity to keep head losses across the sluices to a minimum. This is likely to be economically feasible as discussed in Sect. 2.5.7.4.

In conclusion, tidal power by its very nature is a reliable and predictable energy producer. Forcing it to produce power on demand has proven to be economically counter productive. Moreover, it has been shown that a fixed pattern of plant operation is desirable for environmental reasons, see Sect. 2.5.6.1.6. Therefore, a TPP should *consistently* be operated to maximize energy output. It will depend on site conditions which of the four types of TPPs is most suitable.

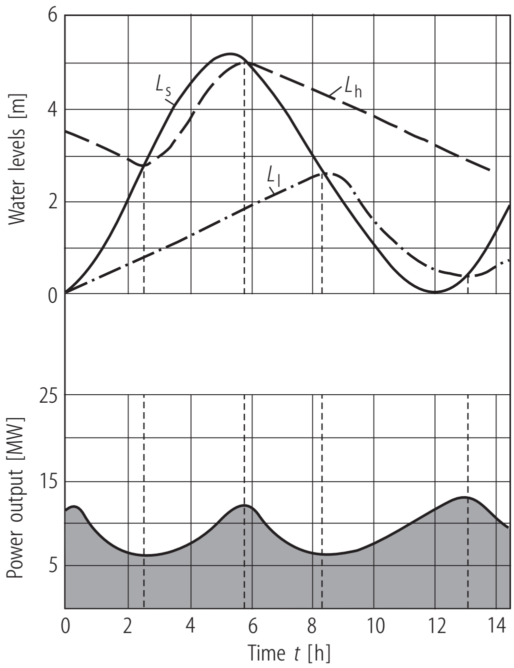

Fig. 2.5.7. Operating mode for a linked-basins TPP using the Decoeur cycle, giving continuous power plus fuel-displacement energy [97Ber, p. 36].
Top: *Operating cycle*. L_s - sea level; L_h - high basin level; L_l - low basin level.
Bottom: *Power output curve*.

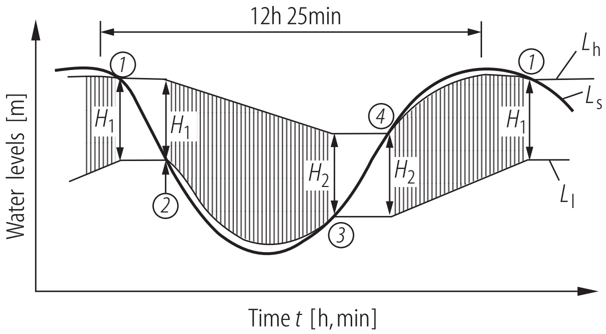

Fig. 2.5.8. Operating mode for a linked-basins tidal power plant with large sluicing capacities, showing water elevations at sea, in the high- and in the low-basin vs. time. L_s - water level on sea side of barrages; L_h - water level in high-basin, L_l - water level in low-basin, *(1)* - sea does no longer replenish water in the high-basin, sluicing & turbining stop; *(2)* - low-basin can start shedding water into the sea, turbining and sluicing start; *(3)* - low basin can no longer shed water into the sea, turbining & sluicing stop; *(4)* - sea can start to replenish water in the high-basin, sluicing & turbining start; *H1* - turbining head at end of "incoming tide" cycle and at start of "outgoing tide" cycle. (All the turbining from high- to low-basin.)

2.5.4 Preliminary assessment of the annual energy potential of single-basins TPPs

A *plain and simple computer-modeling technique* as presented herein is based on two well known formulae from the hydro power mathematical arsenal, with all symbols and units as in Table 2.5.1:

$$P = \rho\, g\, Q\, H\, T_e /1000, \qquad (2.5.7a)$$

which can be re-written as

$$Q = 1000\, P / \rho\, g\, H\, T_e. \qquad (2.5.7b)$$

Formula (2.5.7) applies to the operation of the turbine-generator units.

$$Q = C_D \cdot F \cdot \sqrt{2gH}\ . \qquad (2.5.8)$$

Formula (2.5.8) applies to both sluices and turbine-generators as represented by the hill-chart shown in Fig. 2.5.9.

By way of example, consider a TPP equipped with one or more *double-regulated* turbine-generator units of the bulb type, which means that units are fitted with Kaplan runners and adjustable wicket gates. The units are assumed to have the following characteristics as would be provided by their manufacturer:

- Rated power P_{rated} = 6400 kW;
- Runner diameter D = 5.35 m (like the La Rance machines), hence F = 22.48 m^2;
- Rated head H_{rated} = 3.78 m;
- Rated discharge Q_{rated} = 271 m^3/s;
- Hill chart as shown in Fig. 2.5.9.

With the rated values for P, H and Q known, the hill chart defines for each and every point the efficiency at which the units operate at that point.

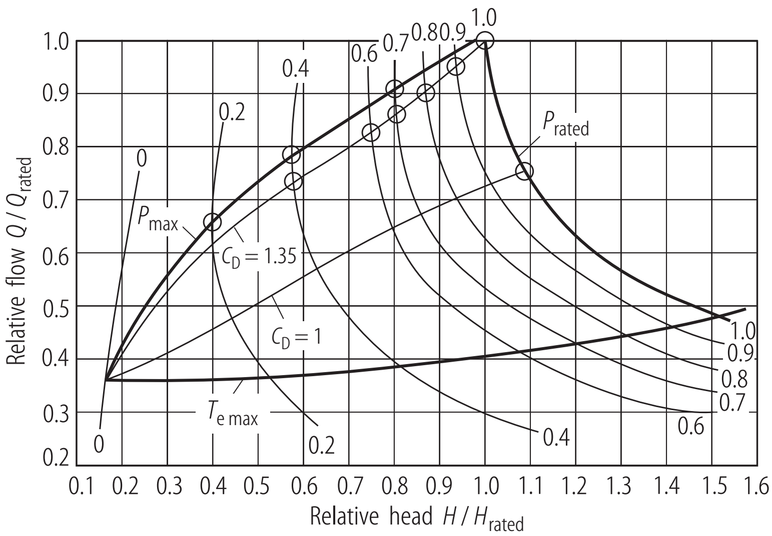

Fig. 2.5.9. Performance chart for double-regulated turbine-generator. P_{max} - maximum power line; $T_{e\,max}$ - maximum efficiency line; P_{rated} - rated power line. The curved lines marked 0, 0.2, 0.4, 0.6, 0.7, 0.8, 0.9 and 1.0 denote constant output in terms of P_{rated}. The line connecting all points on which C_D is constant and equal to 1.35 (1.0) was defined and denoted C_D = 1.35 (C_D = 1). Along these lines, the value of T_e varies from point to point as can be derived from the chart. The line P_{max} appears to correspond to a line of constant $C_D \approx 1.4$ [77Bay, p. 162].

In modeling the operation of the TPP, the optimum route of travel through the hill chart is to be found from a minimum starting head, here assumed to be 1.9 m, to the rated head and beyond. With reference to Fig. 2.5.9, any route within the boundaries of the P_{max} -, $T_{e\,max}$ - and P_{rated} -lines is permitted.
In a conventional hydro plant with limited water resources, one might prefer to travel from low heads to the larger heads along the "maximum efficiency" line. For single, high-basin tidal power plants, however, it has been shown at La Rance and in numerous feasibility studies that the most energy per operating cycle is obtained by moving through the hill chart along the P_{max}-line and then along the P_{rated}-line to heads in excess of the rated head. When the head across the turbines grows smaller again, the travel is back to smaller heads along the same route. To become familiar with the P_{max}-line, the discharge coefficient C_D and the units' efficiency T_e were calculated for a number of the intersection points of this line with the "constant output" lines of 0.2, 0.4, 0.7 and 1.0 times P_{rated} and assembled in Table 2.5.2. This indicates that the P_{max}-line is a line along which C_D is approximately equal to 1.4. Similarly it can be established that other lines of travel can be defined by a constant discharge coefficient such as C_D = 1.0 as shown on Fig. 2.5.9.

Travel from a low head up to the rated head is governed by the formulae (2.5.7) and (2.5.8). In order to maximize the energy output for a single, high-basin TPP, the discharge coefficient C_D should be chosen close to 1.4 in order to travel close to the path of maximum power output. For other types of TPPs, smaller values of C_D should also be considered.

Table 2.5.2. Discharge coefficient C_D and the units' efficiency T_e for several "constant output" lines.

Constant output line	Discharge coefficient C_D	Efficiency T_e
0.2 P_{rated}	1.44	0.47
0.4 P_{rated}	1.44	0.55
0.7 P_{rated}	1.41	0.60
1.0 P_{rated}	1.40	0.61

Once arrived at the "generator limiting capacity" line, the travel goes on along that line with $P = P_{rated}$. From the hill chart the average efficiency at which the units will be operating along the relevant segment of the $P = P_{rated}$ line can be derived. With T_e established, formula (2.5.7a) will provide Q for every known value of H. Knowing Q, the varying water levels in the tidal basin(s) can be calculated. This modeling technique might best be explained by means of a couple of applications.

2.5.4.1 Application of the modeling technique to a single, high-basin TPP

2.5.4.1.1 Geography and hydrography of the chosen site

The hypothetical site chosen for a single, high-basin scheme has characteristics, assumed to be as follows:

- R_{mean} = 5.64 m;
- R_{max} = 6.46 m;
- MWL = + 7.00 m;
- MLW = + 7.00 – 2.82 = 4.18 m;
- MHW = + 7.00 + 2.82 = 9.82 m;
- HHW = + 7.00 + 3.23 = 10.23 m.

The tidal power potential of a site being proportional to the square of the tidal range, it has been argued that in calculating the annual tidal energy output of a given site, the root-mean-square tidal range for that site should be used. This however will result in too optimistic an estimate since, due to the generators' limiting capacity, the peak of spring-tide generation is shaved off. A more cautious approach is therefore to base the annual energy output on a calculation, based on the mean tidal range of the given site.

Assume a semi-diurnal tide of sinusoidal shape. With a duration of one tidal cycle of 12 h 25 min, i.e. 44700 s,

$$L_s = 7 + \sin[2\pi \cdot (t + 11175)/44700] \cdot R_{mean}/2\,. \qquad (2.5.9)$$

From the hydrographic chart it is estimated that

$A_h = 1.65\ km^2 = A_{HHW}$ with water at El. 10.23,
$A_h = 1.125\ km^2 = A_{h(6)}$ with water at El. 6.0,
$A_h = 0.44\ km^2$ with water at El. 4.18.

For this basin, $E_{nat/year} = 0.7\,A\,R^2$ or $0.7\,A_{HHW}\,R_{max}^2 = 48$ GWh, see (2.5.6). Between El. 6.0 and El. 10.23, the surface area of the basin in [km^2] is assumed to vary linearly as a function of the water level L_h of the basin:

$$A_h = [1.125 + (1.65 - 1.125)/4.23 \cdot (L_h - 6)]. \qquad (2.5.10)$$

This being a high-basin TPP, L_h is not expected to fall below El. 6.0.

2.5.4.1.2 Sluicing

Assume 25 fully submerged venturi sluices with throat openings 5 m wide times 3 m high. Assume that 5% of the sluicing capacity is under routine maintenance. The available sluice capacity has therefore a throat area $F_h = 0.95 \times 25 \times 15 = 356.25\ m^2$. The flow Q_{sh} in [m^3/s] from the sea to the high basin is now according to formula (2.5.8):

$$Q_{sh} = C_{DC} \cdot F_H \cdot \sqrt{2gH_{sh}} \cdot f_h\,, \qquad (2.5.11)$$

where f_h is a factor equal to 1 when the sluices are in operation, and equal to 0 when closed. The sluicing discharge coefficient C_{DS} will be assumed to be 1.35 (When filling the basin, it would be possible to use the turbine in its orifice mode but this has been ignored since its practicality depends on the tidal phase difference between the intake sluices and the turbine which is, at the time of writing, not known).

2.5.4.1.3 Power generation

Assume one turbine-generator unit as described above and by Fig. 2.5.9. As long as this unit operates at less than its generator limiting output, the flow Q_{hs} in [m^3/s] through this one turbine is, according to (2.5.8), defined as

$$Q_{hs} = C_{Dt} \cdot F_t \cdot \sqrt{2gH_{hs}} \cdot f_t \,. \tag{2.5.12}$$

To make certain that we stay within the prescribed boundaries yet close to maximum power output, C_D is chosen to be 1.35. The throat area F_t of the turbine remains 22.48 m^2 and f_t is a factor equal to 1 when the turbine is in operation and equal to 0 when idle. The power output P in [kW] according to (2.5.7) is now

$$P = \rho\, g\, Q_{hs}\, H_{hs}\, T_e \,/\, 1000. \tag{2.5.13}$$

If and when the point on the hill chart is reached where $P = P_{rated}$, P becomes constant = 6400 kW. Q is then derived from (2.5.7a).

2.5.4.1.4 Change in water level L_h of high basin

It has been assumed that the water level of the basin will be horizontal under all operating conditions. The step by step raising or lowering of the basin's water level will then be in accordance with

$$\Delta L_h = (\, Q_{sh} - Q_{hs}) \,/\, A_h. \tag{2.5.14}$$

2.5.4.1.5 Building and operating the model

The relevant constants, assumed initial values of some variables, formulae (2.5.9) to (2.5.14) and calculated values of other variables for $t = 0$ were entered into an Excel spread-sheet. The model was arranged to run on constant water levels for the duration of time intervals of 60 seconds. At the end of each time interval the water levels are re-calculated and kept constant for the next time interval. Every 60 seconds there is also an opportunity to change the operating parameters to indicate that from that point onwards, sluices are to be open or closed, the turbine to be operating or idle or the path to be followed through the hill chart changed from the C_D = 1.35 line to the P_{rated} line or vice-versa. If and when changing from C_D (constant) to P (constant) operation, the assumed value for T_e should also be adjusted. At the end of the computer run at $t = 44700$, the water level in the basin should be identical to that at the beginning $t = 0$. If this is not the case, then by trial and error other basin water levels at $t = 0$ should be considered until L_b at $t = 0$ equals L_b at $t = 44700$.

Power output and generated energy are computed for each 60 second interval and the total amount of energy produced is accumulated throughout a generating cycle of 12 h and 25 min or 44700 seconds. The operating mode as calculated for the assumed TPP is presented in Fig. 2.5.10, being a specific version of Fig. 2.5.4b without the pumping option. The energy output per R_{mean} tidal cycle was found to be 22662 kWh which amounts to 705.5·22.662 MW = 16 GWh per year. This would be 33% of the natural energy potential of this basin which was estimated at 48 GWh. The points of discontinuity are identified on Fig. 2.5.10 by vertical lines on the time scale. The numbers of High-Basin Excel files, containing all information relating to the TPP's operating model between points of discontinuity, are shown on a horizontal line just above the time scale.

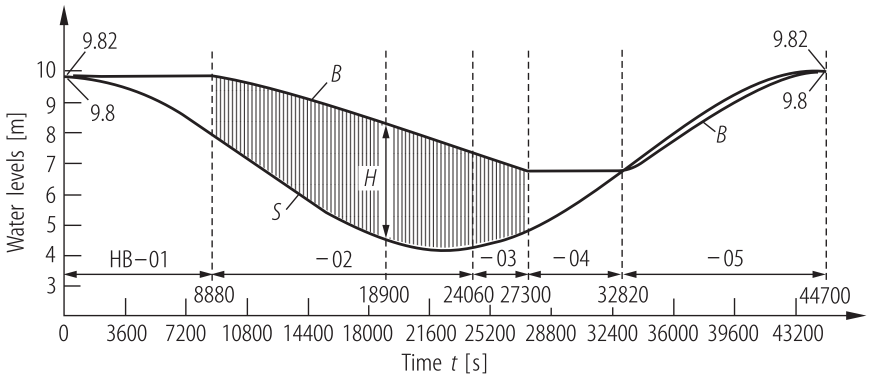

Fig. 2.5.10. Diagram showing the mode of operation through one R_{mean} tidal cycle of a single, high-basin TPP. *S* - sea level; *B* - basin level; *H* = 3.74 m - maximum head on the turbine. The rated head for the unit being 3.78 m, the unit will not be working at its generator limiting output. At t = 8880 s, the turbine starts operating at its assumed minimum operating head of 1.9 m. Power generation stops at t = 27300 s when the generating head has come down again to 1.9 m. At t = 32820 s, the reservoir starts to fill up again in preparation for the next operating cycle.

2.5.4.2 Application of the modeling technique to a single, low-basin TPP

The above model, with minor modifications, would provide the required answers leading to an operating mode as generically illustrated in Fig. 2.5.4c without the pumping option.

2.5.5 The economic value of tidal energy

The recommended way of assessing the value of a contemplated new power generating facility is to plan an extension to the system with and without that specific facility. In comparing alternative ways of meeting the projected total demand, based on the cost of capital, fuel and operating costs over an extended period of time, the most economic solution will become apparent. Environmental costs of each alternative would also have to be assessed.

As concluded in Sect. 2.5.3, a TPP should be recognized for what it is, an *energy* producer. When designing TPPs for maximum energy production, it was shown in Sect. 2.5.4 that some types of TPPs spread their production more evenly throughout the day than others. This then is a legitimate way of easing the absorption of tidal energy into an electric utility system. But even then, each day there will be periods of no tidal power and the weekly fluctuations between neap and spring tides are to be accepted as they come.

Each type of electrical power producer has its peculiar properties, the one being typically a base-load provider such as a nuclear fission plant, the other an energy producer such as a “run-of-the-river-plant”. The latter is in power system parlance referred to as a *must-run-plant*. If the plant does not run when water is available, then that water will have to run to waste. In the same way a TPP which for environmental reasons is operated according to a fixed pattern has to be accepted as a must-run-plant. Hydro with ample storage can readily respond to all types of demand and is a good match for tidal power. Gas turbines are equally capable of responding to a fluctuating demand and in that way complement the output of a TPP. In some areas, tidal power potential exists near active or potential natural gas fields. (Australia’s NW coast, North America’s Maine, New Brunswick and Nova Scotia Atlantic coasts). Tidal power and gas turbine generation make for a good mix in a utility system. With a timely development of the tidal power resources, the energy self-sufficiency of these areas can be greatly extended over time. In addition, there are energy storage systems to be considered.

The presence of tidal power also should make it possible to serve certain energy-intensive industries. This would apply in particular to certain simple yet energy intensive processes like the manufacture of hydrogen and oxygen through electrolysis or the desalination of sea water. In these instances, the potential TPP should be seen as an integral part of the planned industrial facility. The whole facility should then be planned with and without the tidal power source and the alternatives compared, again taking environmental factors duly into account.

During the commemoration of the 30th anniversary of the La Rance TPP, EDF reported that the cost of energy produced by the La Rance plant was well below the average of the EDF system [97Hou]. This illustrates the fact that capital intensive projects compare the more favorably with competing, less capital intensive projects, the more liberally the planning time horizon is chosen.

2.5.5.1 Economic fringe benefits

Aquaculture and agriculture will both reap immediate benefits from a TPP. The former due to the creation of a water basin or basins, protected from the ocean's wave action, the latter due to the protection provided to lands against flooding. The Annapolis TPP in Canada as well as the Jiangxia TPP in China were built as supplements to projects initiated to protect agricultural lands from flooding.

Tourism is drifting away from passive sitting-on-the-beach-soaking-up-the-sun to an active, purpose oriented and educational quest. Both energy and environment are typical subjects capable of attracting the public. A pilot TPP as suggested in Sect. 2.5.9 could be designed as a show-case for public viewing. The Annapolis plant does attract tourists in large numbers to view professionally designed displays and models, the latter being defined as small imitations of the real thing. A pilot TPP would be even more attractive to curious visitors if the plant itself were to be designed for access and viewing by the public. Real turbines and fish can all be brought within view of the visitors if the design engineers, assisted by biologists and architects, set their collective minds to it. Apart from stimulating tourism, the real purpose is to de-mystify tidal power, show its positive aspects and underline its substantial potential as an energy producer. A display would show how the few remaining problems are addressed through this pilot plant.

Recreation could become a substantial fringe benefit, brought about by the construction of a TPP as is clear from the La Rance experience. Sailing, fishing and other water sports will get an opportunity to flourish behind the shelter from ocean waves provided by the TPP's barrage.

Transportation may well prove to be the most important fringe benefit associated with a TPP. Today's residents of Dinard, St. Servan and St. Malo in Brittany would not like to do without the La Rance TPP. Motorized traffic, flowing over this barrage, crosses the La Rance estuary while taking the TPP for granted. This in itself is another compliment for the way EDF's engineers designed the La Rance plant.

2.5.6 Tidal power engineering since the 1960's

Numerous articles in power-, electrical-, mechanical- and civil engineering magazines have reported on tidal power prospects and developments around the world. A practical summary on the subject is provided in [97Ber] and [91Bak]. An update on tidal power experiences and prospects is presented in [97Hou], being the proceedings of the symposium organized to commemorate the 30th anniversary of the La Rance TPP and covers the tidal power scene in France, Canada, Great Britain, Korea and Russia. An article of similar scope, reviewing tidal power prospects in numerous countries around the world is [97Hou]. References [98Nov], [98Usa1], [98Usa2] and [98Kar] together provide the proceedings of a symposium organized to commemorate the 30th anniversary of the Kislogubsk TPP on the Barents Sea. This series of articles presents some of the lessons learned from operating a TPP in the arctic. Following are short descriptions of tidal power projects which have been built and operated over a number of years.

2.5.6.1 The La Rance TPP

2.5.6.1.1 Purpose

Electricité de France (EDF) chose the La Rance river estuary as the site for a full-scale environmental TPP where equipment, design, construction and operation could be studied [97Ber, p. 230].

2.5.6.1.2 The site

The La Rance river flows into La Manche (the English Channel) to the west of St. Malo. The river estuary, upstream from the location of the tidal power barrage, extends inland for 21 km and has a water area varying between 4.75 and 22.06 km^2. The tide is regular semi-diurnal with a tidal range fluctuating from 3 to 13.5 m. The 13.5 m tide has a probability of occurrence of once in 28 years. Mean neap tide has a range of 5 m, mean tide of 8.5 m and mean equinoctial spring tide of 11.36 m.

2.5.6.1.3 The plant

The La Rance tidal power plant, as built, is located 4 km inland from the sea, thus protected from strong wave action. The total length of the plant is 750 m and crosses the small rocky Chalibert Island, see Fig. 2.5.11. An aerial photograph of the plant is shown in Fig. 2.5.12. The 225 kV switchyard was located on the left bank. The various parts of the plant proper, from left bank to right bank, consist of the shipping lock (65×13 m with sill elevation at +2 m), the powerhouse (332.5×53.5 m), an embankment 163.6 m long and 25 m high, consisting of rock fill with a concrete core and the sluice structure (115×35.5 m), connecting Chalibert Island with the right bank.

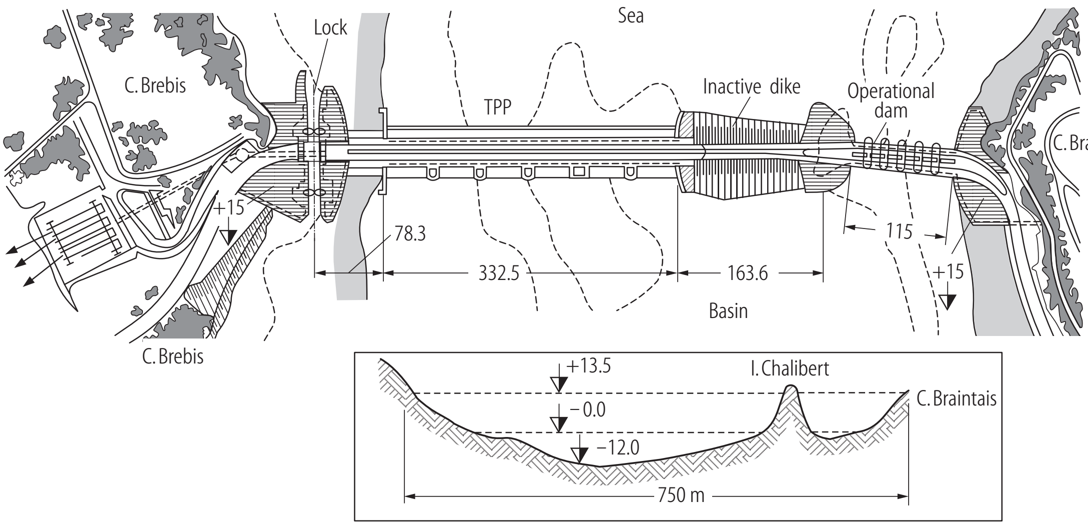

Fig. 2.5.11. Plan view of the La Rance tidal power plant with profile along the centre line of the barrage prior to its construction [97Ber, p. 231].

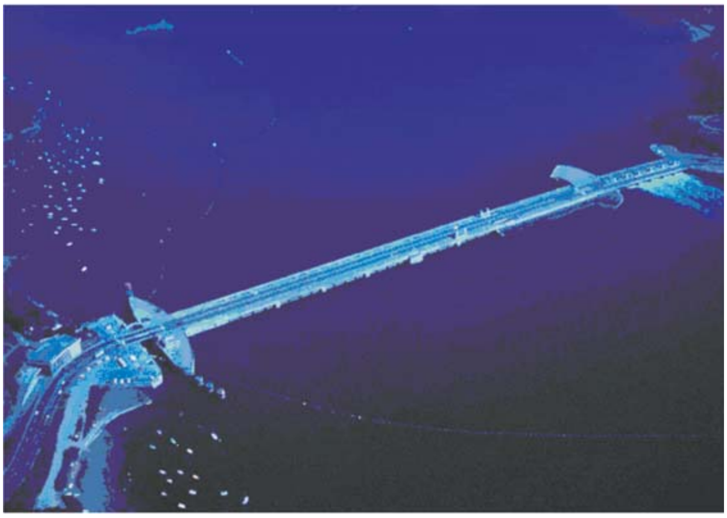

Fig. 2.5.12. Aerial view of the La Rance TPP, courtesy of EDF [97Ber].

During the study phase for the La Rance plant, EDF stimulated the development of the horizontal-axis bulb turbine. This type of machine, placed within a *horizontal* water passage and a drastic departure from normal practice during the fifty's which still generally used vertical axis machines in vertical water passages, greatly simplified the plant layout and civil engineering design and provided a higher hydraulic efficiency.

The powerhouse between shipping lock and embankment appears to a visitor as a long tunnel of reinforced concrete, 19 m wide with a vaulted roof, see Fig. 2.5.13. It is equipped with 24 bulb-type turbine-generator units, each with a rated generator output of 10 MW. At their time of installation, the bulb units of the La Rance plant were truly state-of-the-art machines, the result of extensive research and full-scale model tests of innovative ideas. The La Rance machines were designed to generate power on either the incoming or outgoing tide, to pump at periods of slack tide either into or out of the basin and to serve as orifices, passing water either into or out of the basin when the head across the plant is insufficient for power generation.

The 24 turbines are of the Kaplan type with a diameter of 5.35 m and four blades. The turbines rotate at a speed of 94 rpm. Their runaway speed is 260 rpm. The alternator is directly coupled to the turbine and housed within the bulb. The rated net head of the machines, i.e. the minimum head at which the rated output (= maximum output) can be obtained is 5.65 m in direct generation (i.e. basin-to-sea) and 7.00 m in reverse generation (i.e. sea-to-basin). The rated discharge of the machines is 275 m^3/s.The maximum net head is 11.00 m in either direction. The flow of water through the turbine can be regulated by means of the distributor with 24 adjustable vanes. The overall length of bulb and turbine is 13.4 m.

The sluice structure accommodates six sluices, each with a throat opening 10.00 m high and 15.00 m wide. The gates were designed to open and close in accordance with the diurnal tidal regime 705 times annually under all conditions of the differential head. Wheels were provided to enable the vertical movement of the gates up and down the gains. For further details refer to [66All].

2.5.6.1.4 Construction

With many innovations introduced with its state-of-the-art machinery, the civil engineering design was approached in a conservative way and reached back to proven ways of building a low-head hydro plant on a river. The designers stipulated that the plant was to be constructed in the dry so as to assure quality from the foundation rock surface up, all in accordance with proven practice. The challenge to construct extensive cofferdams in the deep, fast flowing tidal waters of the site was met by the dam builders with great skill, imagination and perseverance but at a high price. The 24 La Rance units were commissioned during 1966.

2.5.6.1.5 Operation

When, after great efforts in overcoming numerous design and construction challenges, the plant was partially commissioned in 1966, its proponents were keen to prove its worth. The maximum flexibility provided in both turbine-generator units and sluices enabled EDF to experiment with all possible ways of operating the plant. The double effect machines provided the choice to generate on either the incoming or the outgoing tide. The machines' pumping capability provided the opportunity to top off the basin just prior to a generation sequence from basin to sea or to lower the basin prior to a generation sequence from sea to basin. Finally the machines could be used as orifices, in tandem with the sluice gates. During the first few years, the plant's operation was aimed at yielding the maximum possible return on investment.

J. Cotillon of EDF provides an illuminating summary of how the plant's operation developed during its first six years of active service [74Cot]. As machines were being commissioned and teething problems resolved, availability of the machines developed as shown in Table 2.5.3.

Up to 1970, pumping was hardly used due to the inadequacy of the transmission system in Brittany to provide the suitable energy input. The power transmission network was improved in late 1971 allowing more pumping but not as much as an optimum plant operation would require. From the end of 1971 to July 1975, the evolution of the operating pattern featured an increase in direct pumping and a related decrease in reverse generation which was less and less considered for the middle-range tides and mainly reserved for spring tides. Table 2.5.4 illustrates this development.

This change in operating procedures resulted in an increase of the net energy output as shown in Table 2.5.5. During these early years, the plant operators tried to respond to the demands of the market by advancing or delaying the start of the generation cycles. Cotillon points out that such procedures resulted in big energy losses. By 1974, there were still restrictions on the amount of energy that could be drawn from Brittany's transmission system to allow pumping at the most advantageous periods. Cotillon estimated that the net output of the pumping operation could be increased from 120 GWh to 230 GWh if pumping power of up to 150 MW could be provided whenever called for. This would raise the net output of total energy to 617 GWh per year.

In July 1975 it became apparent that as a result of the frequent asynchronous start ups of the machines, some connections within the generators had become over-stressed. Over a period of seven years, from 1975 to 1982, each of the 24 generators was strengthened. During this period, availability factors ranged from 71 to 94% [86Hil]. As of July 1975, operating procedures were simplified: Only direct generation was allowed, without pumping. As a result, the net generation output for 1975 was 482 GWh, for 1976 438 GWh and for 1977 456 GWh. Some pumping was resumed during 1972.

Table 2.5.3. Availability rates of turbine-generator units of the La Rance TPP from 1968 to 1974.

Year	1968	1969	1970	1971	1972	1973	1974
Availability [%]	77	84.5	93.3	94	93.9	95.17	95.54

Table 2.5.4. Evolution of the operating modes of the La Rance tidal power plant from the year 1970 to 1975, expressed in %.

Year	1970	1/1/1975 to 6/1/1975
Direct generation	36.36	46.14
Reverse generation	13.50	3.17
Direct pumping	5.30	15.90
Reverse pumping	0.98	0.11
Orifice (sluicing)	11.99	13.96
Standing idle	31.87	20.72
Total percentage	100.00	100.00

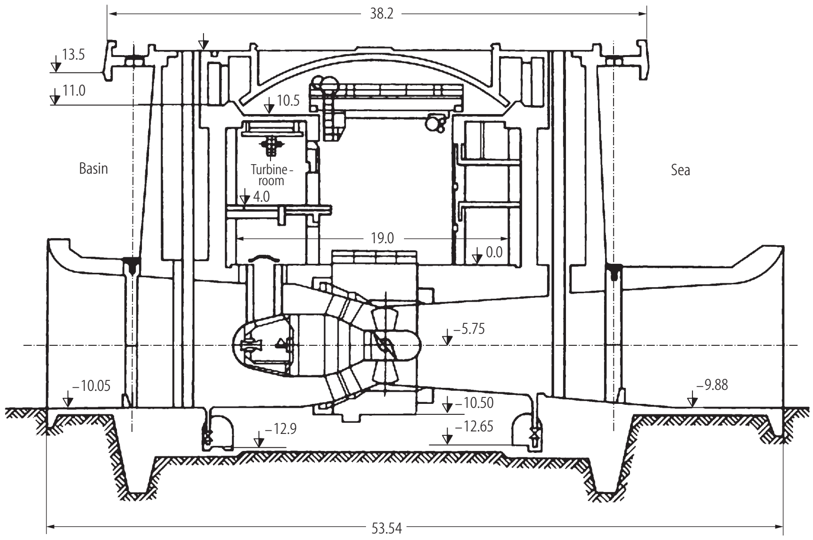

Fig. 2.5.13. Cross section of the La Rance TPP along the axis of a turbine-generator unit [97Ber, p. 232].

Table 2.5.5. Breakdown of energy between true tidal energy and that generated from pumped storage.

Year	1972	7/1/1973 to 1974	1974
True tidal energy [GWh]			
Gross output	414	414	414
Plant losses & consumption	29	29	27
Net output	385	385	387
Pumping energy [GWh]			
Input	60	70	90
Gross output Pumping	168	187	210
Efficiency [%]	280	265	233
Net output	108	117	120
Total energy [GWh]			
Net output	493	502	507

Based on the early operating experience with the world's first major tidal power plant, Cotillon offers some general comments:

1) In order to obtain the maximum possible amount of energy from a tidal power plant, there is an optimum generation pattern. Any deviation from that pattern results in big energy losses.
2) With the availability of tidal tables and forecasts of energy demand as a function of time, there was a tendency to plan generation sequences two weeks in advance at La Rance. In order to obtain the maximum possible amount of energy however, the exact time of starting or stopping a generation sequence should be governed by the head on the turbines which in practice will always occur at a time different from the predicted time.
3) The search for dependable capacity from the La Rance plant always played a role in choosing the operating pattern for the plant. The operators of the plant were not fully aware of the energy losses involved in deviating from the operation pattern which maximizes the output.
4) When operating for maximum energy production, Cotillon estimated that the La Rance plant should be capable of producing 530 GWh per year of true tidal energy. This would be approxi-

mately 27% of the natural energy $E_{nat/year}$ of the La Rance basin, which is 1987 GWh per year according to (2.5.6) with A = 22 km^2 and R = 11.36 m.

5) Pumping for a single-basin plant like La Rance should play a major role in energy generation.
6) With no time restriction on receiving 150 MW of power for pumping, it should be possible to raise the net output of the plant from 530 GWh to (530 + 230) GWh = 760 GWh.
7) Notwithstanding his emphasis on energy production, Cotillon observed that: "Anybody concerned with tidal power studies is fully aware that the future of tidal energy hinges on producing firm power economically." To the writer, this seems to be a reflection of the common wisdom of the day which postulated that there must be a capacity benefit to tidal energy generation to justify its high capital cost.

As the completion of the generator renovation program approached, it was time to re-define optimum operating procedures. By 1982, the La Rance plant was back in normal operation and guided by updated operating procedures, the true tidal energy output changed from the 1974 figure of 387 GWh to 511 GWh in 1982, 503 GWh in 1983 and 494 GWh in 1984. The total net energy output in 1984 was 601 GWh, i.e. 494 GWh of true tidal energy and 107 GWh from pumped-storage. During 1984, the emphasis of plant operation shifted towards single-effect operation, generating energy on the outgoing tide from basin to sea. During the higher tidal ranges there was some double-effect operation with turbining in both directions. Direct pumping was done near the neap tidal ranges. The way in which the 24 bulb machines were used through the year 1984 is summed up in Table 2.5.6. Of the total number of machine hours available during that year, i.e. 365×24 hours×24 machines = 210240 machine hours, 157500 hours or about 75% were spent in active service while the machines were idle for the remaining 52740 hours or about 25% of the time. Similar data for the year 1994 were obtained from [97Bos] and are shown in the same Table 2.5.6. The division between active and idle time remained the same, 75% and 25%. The main change in operating procedures from 1984 to 1994 was the almost doubling of time spent in reverse turbining. During the higher tidal ranges, double effect operation became the norm.

After thirty years of experimentation with the La Rance plant, operating within the EDF system, the single effect operation from basin to sea combined with double effect operation during periods near spring tides and direct pumping from sea to basin near neap tides was found to be the preferred operating mode. For any tidal power plant in any power system, it are the criteria imposed by prevailing technical, economic and environmental conditions which will determine what type of plant should be chosen and how that plant should be operated. By 1994, environmental considerations did not yet affect the choice of optimum operating mode.

By 1996, the machines had been in continuous operation under severe conditions for thirty consecutive years. A renovation program of all 24 machines was started in 1997. The machines' original design concept is being preserved so that they will maintain their wide range of capabilities, i.e. turbining as well as pumping in the direct or reverse mode and serving as sluice orifices.

Table 2.5.6. Assignment of tasks to the 24 bulb machines of the La Rance TPP between 1984 and 1994.

Tasks	Working time in machine hours		Percentage of working hours [%]	
	1984	1994	1984	1994
Direct turbining, basin-to-sea	91350	90132	58	57.5
Reverse turbining, sea-to-basin	4725	8470	3	5.4
Direct pumping, sea-to-basin	28350	27811	18	17.7
Reverse pumping, basin-to-sea	0	0	0	0.0
Orifice sluicing, generally sea-to-basin	33075	30427	21	19.4
Total	157500	156840	100	100.0

2.5.6.1.6 Environment

During the planning and construction phases of the La Rance plant, environmental considerations were secondary to those of a technical or economical nature. In 1976, ten years after the start-up of La Rance's first turbine-generator unit, a law to protect nature was passed by the French Government. During construction of the plant, the La Rance estuary had been isolated from the ocean during a three year period from 1963 to 1966, during which time tidal movements within the basin were suppressed, salinity profiles were drastically changed and appreciable sedimentation took place as well as a strong increase in organic matter. The marine flora and fauna of the estuary disappeared almost totally except for certain tolerant species such as mussels. After the plant had been put into operation, fine sediments of marine origin were deposited in coves which were attributed to the long periods of stagnant flow. An environmental assessment stressed that, in order for a new biological equilibrium to develop, regularity in operating the plant would be of utmost importance.

Construction of the La Rance barrage created a basin, protected from ocean swells and waves which has attracted water sports enthusiasts over the years. The 100000 year-round inhabitants of the La Rance reservoir drainage basin are joined by 300000 summer residents. In 1994 an environmentally oriented action group was created, acting under the acronym C.O.E.U.R. (heart): Comité Opérationnel des Elus et Usagers de La Rance [99COE]. Among the various activities of COEUR, the design, calibration and operation of a mathematical model was commissioned to study the hydrodynamic and sedimentation patterns of the La Rance river estuary. These model studies were started in October 1998 [00COE]. At the time of writing this text, early 2001, no definite recommendations have yet been made.

2.5.6.1.7 Cost of energy

At the time of its early operation in 1966, it was realized that the energy produced by the La Rance plant was costly. In 1982, sixteen years after commissioning, the cost was 16.9 ¢/kWh (1 ¢ = .01 French Franc) of which the financial component was 11 ¢/kWh. EDF's nuclear stations generated at 20 ¢/kWh while the best run-of-the-river plants produced at 10 ¢/kWh [87Ano], [84Hil]. When celebrating the 30th anniversary of the La Rance plant in 1996, Alain Barreau of EDF stated that the cost per kWh of energy from La Rance was at that time well below the average of EDF [97Bar].

2.5.6.2 The Annapolis pilot TPP

Purpose
The purpose of the TPP was to provide a full-scale test of the Straflo^{TM} turbine-generator concept in the Fundy tidal environment [82Whi] on Canada's Atlantic coast.

The site
An existing coarse rock-fill barrage, connecting the town of Annapolis Royal with Granville Ferry in the province of Nova-Scotia, was chosen as the site for the plant. The existing barrage had been constructed in 1963 to provide stable water levels above the barrage in order to protect the diked marshlands in the Annapolis River reservoir from flooding during storms and high tides. The barrage passed across Hog's Island. De-watering sluices were located between Hog's Island and Annapolis Royal, see Fig. 2.5.14. The Annapolis river reservoir has a surface area at high tide of $A_{\mathrm{b\,max}}$ = 4.8 km^2. The mean tidal range at the site is R_{mean} = 6.4 m.

The plant
A cross section of the plant is shown in Fig. 2.5.15. The turbine has four fixed blades, the distributor 18 wicket gates. The normal operating head range is 1.4 to 6.8 m. Maximum operating head 7.1 m. The rated head is H_{rated} = 5.5 m, the rated power P_{rated} = 17.8 MW and the rated discharge Q_{rated} = 378 m^3/s. The rated speed is 50 rpm and the runaway speed 98 rpm. The sluices consist of two gated openings, each 9.2 m wide times 7.3 m high, discharging from the Annapolis River reservoir into the tidal waters of An-

napolis basin which are in open connection with the tidal waters of the Bay of Fundy. The sluices were upgraded to serve as filling sluices, passing water in the direction opposite to the one for which they had originally been designed. In addition there is a fish passage, 3 m wide times 7.3 m high at El 1.83 m higher than the sluice openings [81Dou].

Construction
This single-unit TPP was built in the dry by excavating a construction pit on Hog's Island, [81ENR2]. The island consisted predominantly of glacial till so that there were no problems keeping the construction site dry. The plant was commissioned in 1984.

Operation
The unit was designed to operate in single effect, generating power on the outgoing tide from the basin to the sea. Due to the fact that the barrage was originally built to protect agricultural lands from flooding, the maximum basin level was set at 1.8 m above mean sea level. This put a severe restriction on the energy production potential of the machine. The minimum generating head was set at 1.4 m.

Environment
The mortality rate of fish, passing through the turbine, was found to be unacceptably high [86Dad].

Cost of energy
Nova Scotia Power Inc., the present owner of the plant, declined to provide information on energy production and cost.

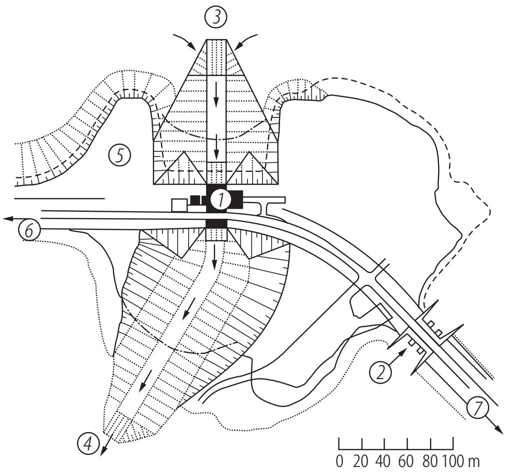

Fig. 2.5.14. Site layout of the Annapolis TPP.
(1) - Powerhouse; *(2)* - Sluices; *(3)* - Annapolis River reservoir; *(4)* - Tidal waters of Annapolis Basin; *(5)* - Hog's Island; *(6)* - to Granville Ferry; *(7)* - to Annapolis Royal (source: Escher Wyss, Zürich).

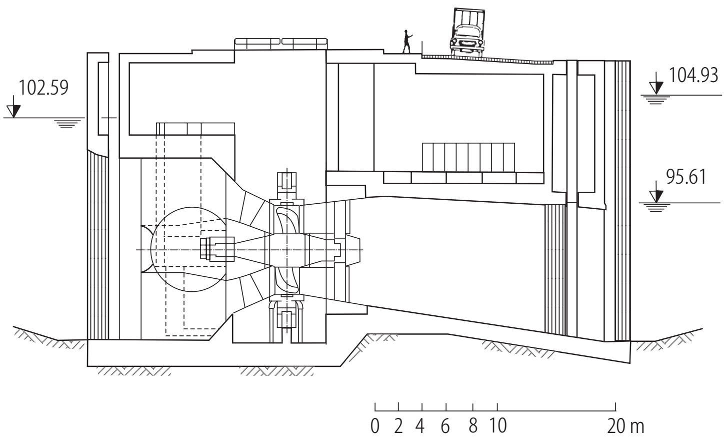

Fig. 2.5.15. Cross section of the Annapolis TPP along the axis of the turbine-generator unit. Diameter of turbine is 7.6 m (source: Escher Wyss, Zürich).

2.5.6.3 The Kislaya Guba pilot TPP

Purpose

This TPP served two different purposes. First, as a proof of feasibility of a construction method, namely the prefabrication of the TPP, floating it in place and placing it on a prepared foundation. Furthermore, it served as an experimental playground for power generating equipment operating at extreme low heads.

The site

Kislaya Guba is a small, deep bay in the eastern rocky shore line of a larger bay, the Ura Guba off the Barents Sea, about 60 km to the west of Murmansk, the major industrial center in Russia's extreme western arctic, close to Finland. The plant was located within the narrow gap which provides access from Ura Guba into Kislaya Guba. This gap is about 35 m wide at low water. The area of the basin at high spring tide is $A_{b\ max}$ = 1.5 km^2. The tide is regular, semi-diurnal, the mean tidal range R_{mean} = 2.27 m with a maximum tidal range R_{max} = 3.23 m.

The plant

The plant consists of a pre-fabricated concrete caisson which was originally designed to accommodate two bulb turbine-generators, see Fig. 2.5.16. One of these units was designed, built and delivered by Neyrpic Alsthom of France. The second unit was to be built in the Soviet Union. However, the design was subsequently changed, replacing the second generating unit with a sluice. For the Neyrpic-Alsthom unit, H_{rated} = 1.28 m and P_{rated} = 400 kW. The Kaplan runner has a diameter of 3.3 m. It is fitted with four adjustable blades. The unit was designed for double effect generation, pumping and sluicing, like the La Rance units. At La Rance however, turbines and generators were directly coupled. The Kislaya turbine is coupled to the generator through a step-up gear, increasing the speed from 72 to 600 rpm.

Construction

Between 1965 and 1968, the plant was built as a concrete caisson, 36×18.3 m in plan times 15.35 m in height, in a construction dock, floated and towed to the site in August 1968, see Fig. 2.5.16, and lowered onto a prepared foundation. With this method of construction, unfavorable site conditions such as strong tidal currents and high ocean waves were avoided. Also, construction can be carried out where labor is available, avoiding the cost of construction camps in isolated localities.

Operation

The one unit was capable of producing 1.2 GWh of energy per year. No data are available on the cost of energy produced. Lessons learned from operating the Kislaya Guba TPP may be found in [98Kar], [98Nov], [98Usa1], [98Usa2] and [96Ste]. On the whole, the plant has lived up to its designers' expectations.

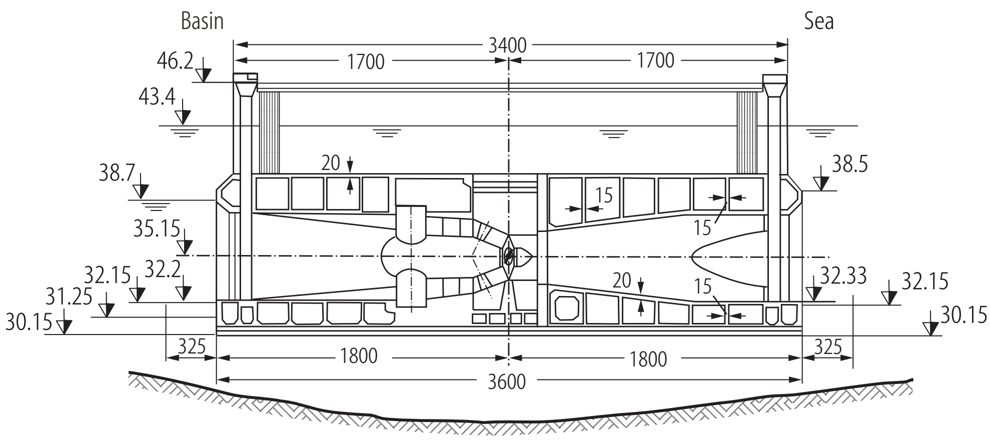

Fig. 2.5.16. Cross section of the Kislaya Guba powerhouse along the axis of the generating unit [97Ber, p. 337].

2.5.6.4 Tidal power applications in China

In 1958, a Chinese national seminar aimed at the promotion of tidal power development and the assessment of tidal power potential in the whole country was held in Shanghai [85Che]. The potential tidal power sites are located along China's East coast from the Liaoning province in the north, adjoining North Korea, to the Guangxi autonomous region in the south, adjoining Vietnam. The most promising sites are to be found in Fujian, opposite Taiwan, and Zhejiang, south of Shanghai. The tides are mostly of the semi-diurnal type. A second seminar was held in 1978 in Wenling in Zhejiang province, its main theme being the Jiangxia experimental TPP, under construction at that time. During this seminar, the total capacity of China's exploitable tidal power resources was reported to be 21600 MW with an annual energy production of 62 TWh. 88% of this exploitable potential was located in Zhejiang and Fujian provinces. Wang Chuankun reported in 1989 [89Wan] that out of a total of 60 small-sized TPPs built since the late fifties, only seven were still in operation. By the year 2001, there were nine plants in operation. Some of the reasons why many plants failed were

- unsuitable site selection,
- improper design,
- inadequate equipment and
- lack of connection with a power grid.

The nine remaining TPPs range in a capacity from 40 to 3200 kW, eight plants are of the single-basin type with either single-effect or double-effect operation, and the one remaining plant is of the linked-basins type. Most of these nine stations are linked to land reclamation projects. Since the late fifties, Chinese engineers have done more experimenting with a larger variety of TPPs than any other nation.

2.5.6.4.1 The Jiangxia experimental TPP

This TPP is located in Zhejiang province, about 200 km to the south of the scenic city of Hangzhou.

Purpose
To gain experience in the design, construction and operation of a TPP and to produce urgently needed energy.

The site
The Jiangxia Bay, a side-branch of Leqing Bay, had been closed off by means of a rock-filled dam with a central clay core by local authorities for land reclamation purposes. In 1972 it was decided to add an experimental TPP to the reclamation project with funds allocated by the central government. The plant was built in the left bank of the Jiangxia inlet as shown in Fig. 2.5.17. The tidal regime is semi diurnal with R_{max} = 8.39 m.

The Plant
For a cross section, see Fig. 2.5.18. The plant operates in double effect for both power generation and sluicing. The first 500 kW bulb unit was commissioned in May 1980, the second, a 600 kW unit, in June 1984. These units do not have pumping capabilities. By the end of 1985, five units were in operation. The third to fifth units each had a rated capacity of 700 kW and were capable of six operating modes, i.e. generating, pumping and sluicing in both directions. The installed capacity with five units amounts to 3200 MW. The installation of a sixth unit has been deferred indefinitely. The minimum operating head of the units is H_{min} = 1.5 m, the rated head is H_{rated} = 2.5-3.0 m. The runners are of the Kaplan type with four blades, D = 2.50 m. Each unit has eight fixed guide vanes and 16 adjustable wicket gates. Turbine 1 and 2 run at a speed of 118 rpm which is stepped up to 500 rpm by means of a planetary gear. Turbines 3 to 5 run at a speed of 125 rpm and are directly coupled to their generators. The sluice structure, also built within the left bank and as part of the original land reclamation project, has five openings 4.2 m high by 3.3 m wide, controlled by reinforced concrete gates.

Construction
The plant was built in the dry within the left bank, behind cofferdams. The first unit was commissioned in 1980.

Operation
The highest basin level is restricted to 1.2 m. The annual energy production amounted to 1.96 GWh. Approximately 3.8 km^2 of land were reclaimed in the basin above El. 1.2 m which were utilized to plant orange trees, sugar cane, cotton and rice. The inter-tidal zone of the basin with an area of 1.2 km^2 is used for oyster culture and clam fishery. The basin area at lowest low water is 0.8 km^2. This basin is used for raising prawns and various kinds of fish. The reclamation activities greatly contributed to the economic benefits of the project [97Ber], [85Che].

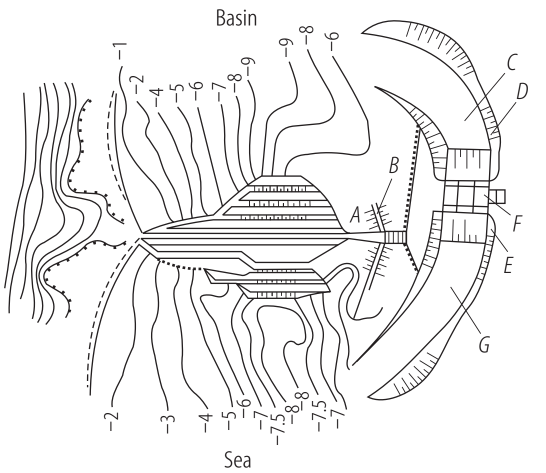

Fig. 2.5.17. Plan view of the Jiangxia single basin, double-effect TPP. *A* - dam, *B* - sluices, *C* - basin-side channel, *D* - powerhouse, *F* - switch yard, *G* - sea-side channel [85Che].

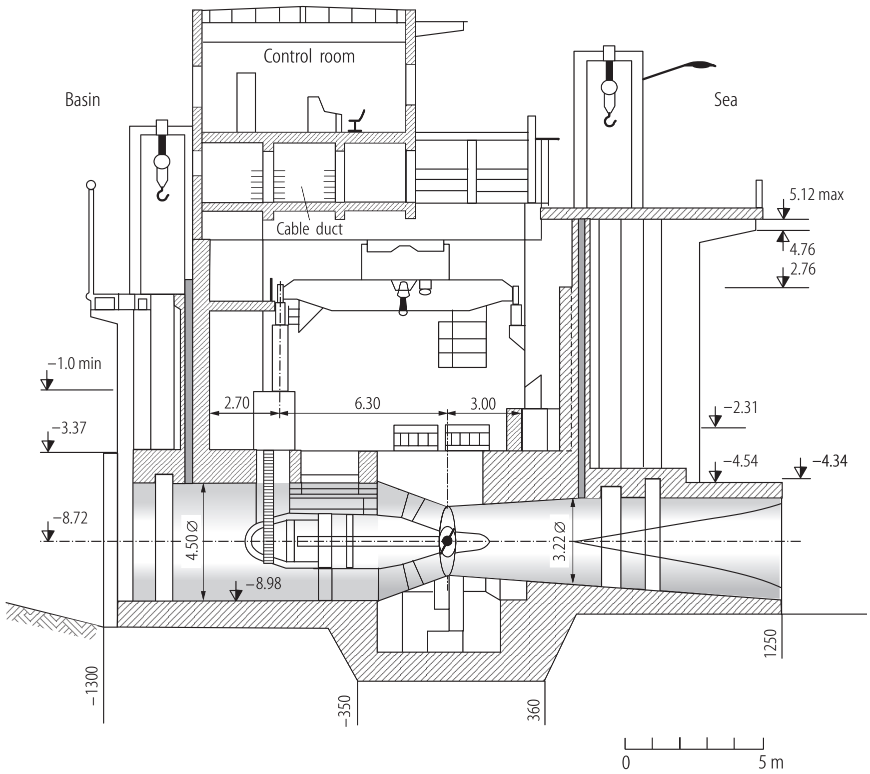

Fig. 2.5.18. Cross section of the Jiangxia TPP along the axis of a turbine-generator unit [85Che], [97Ber, p. 329].

2.5.6.4.2 The Shashan TPP

This TPP was built shortly after the first seminar on tidal power development in 1958. It began as a single, high-basin plant with a wooden turbine, providing mechanical energy for the grinding of grain. In 1964, the wooden turbine was replaced by a steel runner with a matching 40 kW generator. The plant now produces 100000 kWh/year, which is used for irrigation and 860 rural households [85Che].

2.5.6.4.3 The Haishan TPP

This TPP is noteworthy as it is the only linked-basins plant in existence. The plant is located on Maoyan Island in Zhejiang province where it serves an isolated community of 760 families. The plant was designed for two 75 kW units of which only one was installed and commissioned in 1975. The unit operates continually. The energy is used partly to pump fresh water for domestic and irrigation use into the community reservoir. Tidal energy is also supplied for domestic use and for small local industries such as grain processing, agricultural machinery repair, salt production, etc. [86Che].

2.5.6.4.4 The Xingfuyang TPP

Located in the Fujian Province and commissioned in 1989, this single, high-basin TPP is the latest addition to China's TPPs. Installed capacity is 4×320 kW = 1.28 MW, the annual energy production 3.1 GWh. R_{max} = 7.16 m, R_{mean} = 4.54 m, multi-purpose with aquaculture as its main secondary benefit [97Che].

2.5.6.5 Environmentally-oriented pilot TPPs

The La Rance, the Kislogubkaya and Annapolis pilot TPPs were all designed, built and operated to find and test answers to technical questions. Several technical questions still remain to be answered but are within the state of current engineering capabilities and therefore do not need any further pilot-scale experiments. Today's pressing questions are of an environmental nature and before the design of any large-scale TPP is undertaken, answers will have to be found to those questions. Solutions are to be developed and presented in a convincing manner not only to well established and generally recognized problems but also to problems which are by the general public perceived to be serious. In this way, each locality will have its own problems to tackle. While it is too early to plan for major TPPs, small-scale TPPs could be designed, built and operated to demonstrate the feasibility of solving one or more of the problems which figure prominently in a specific locality. Various problems might so be addressed, to name a few:

- *Siltation* has happened in several tidal areas in a big way after the construction of dams. Such dams, if built for the purpose of transportation or agriculture, might well have created large areas of stagnant water resulting, not surprisingly, in large tidal flats. Dams therefore are, in the public's mind, at the root of all siltation problems. Since a TPP will require the construction of dams in tidal waters, TPPs are by definition perceived to have a negative impact on the environment. The big difference when comparing the dams for a TPP with those required for most other purposes is that for a TPP turbines and sluices are installed in great numbers. The basic idea of a TPP is to keep the water moving. Tidal waters continue to be tidal waters. The creation of a tidal power basin may result in the flooding of salt marshes but then there could be areas where water circulation is limited so that siltation would happen in these areas and new salt marshes may again be created. The habitat for shore birds would change but not disappear. Tidal power does not kill but it does change the environment and, if well conceived, for the better.
- *Fish mortality* is not as visible to the public as siltation and is therefore not as prominent in the public mind. Yet it constitutes a far more serious problem since it affects the livelihood of many fishermen and the food supply of the public.

- *Changes in the tidal regime* will occur whenever a TPP is built. By monitoring the before and after situations with pilot-scale projects, a balance of positive and negative effects could be drawn up which should prove useful in planning the major TPPs of the future.

2.5.7 Layout and civil works design of a TPP

TPPs are a special kind of low-head hydro plant. Because of their hydraulic efficiency and simple water-passage configuration, the straight flow type turbine-generators are the preferred kind of power generating equipment for TPPs. This includes bulb, rim-generator-turbine and pit turbine units. To the extent that the machinery dictates the shape of the powerhouse structure, TPPs have much in common with and can greatly benefit from experience gained in designing, building and operating low-head conventional hydro plants. The fact however that TPPs are often built in an exposed ocean environment calls for the need to also take advantage of the wide range of expertise, developed since the second world war, in constructing major structures in the ocean environment. The solution to building successfully in the ocean environment is to avoid fighting the elements during construction and to take advantage of them whenever possible. Oil drilling and production platforms, bridges spanning ocean arms and dams built in tidal waters are all designed to withstand the ocean elements but are by preference put in place when the ocean is calm. In addition to conventional hydro construction expertise, tidal power engineers should refer to such sources as [99Van], [95Van], [89Van], [84Van], [84USA1] and [84USA2]. None of these references, except the first, deals specifically with tidal power engineering but they provide an insight into coastal engineering practices.

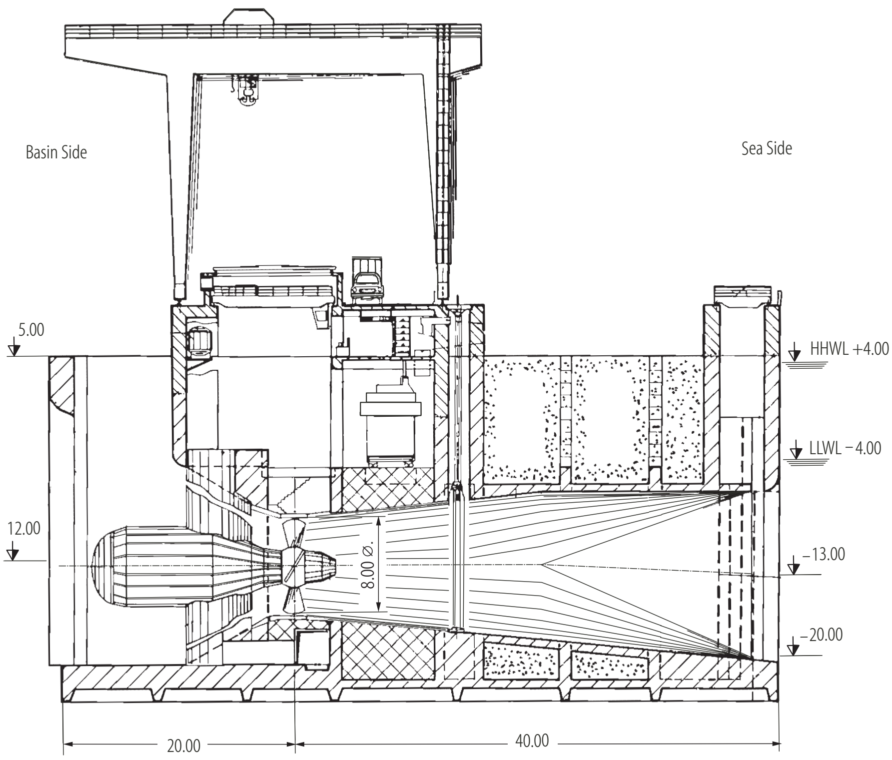

Fig. 2.5.19. Cross section of conceptual design of a single, high-basin TPP on Korea's west coast by French consulting engineers. *HHWL* - highest high water level; *LLWL* - lowest low water level (source: Sogreah, "Garolim Tidal Power Plant, Feasibility Studies" for the Korea Electric Co., 1981).

2.5.7.1 Construction in the dry

Each tidal power site will have its own peculiarities which will determine the optimum choice of construction methods. When opting for construction in the dry, power plant design and construction practices are similar in all respects to conventional, low-head hydro plant design and construction.

2.5.7.2 Construction in the wet

Construction in the wet, or parts thereof, should be considered when

- major portions of the plant are to be built in an area exposed to ocean environment;
- a great number of repetitive construction operations are to be performed.

To a large extent, the terminology is a misnomer since the basic idea is to undertake most of the construction on dry land under closely controlled conditions. Such construction would be carried out in a dry-dock or on a slipway. The pre-fabricated elements would then be floated out and placed in their permanent position when conditions of climate, tide and currents are favorable, thus reducing the “in-the-wet” activities to an absolute minimum.

With the exception of Kislaya Guba, no TPPs have been built in the wet, but numerous preliminary designs, intended to be executed by means of pre-fabrication, have been prepared [97Ber], [91Bak], [80Sir], [80Tay], [77Bay]. Figure 2.5.19 shows a typical example. At a site like La Rance, prefabrication would in the 21st century be used in constructing such a barrage. French engineers from the Alsthom-Atlantique shipyards in Saint Nazaire, Brittany were the first to apply the prefabrication of hydro power plants on a large scale [81ENR1]. In 1980/81 they prefabricated the three 24 MW unit W.T. Love Power Plant in their shipyard and in 1981 transported it across the Atlantic Ocean on a semi-submersible, self-propelled barge to Baton Rouge, LA on the Mississippi river. From there, the plant floated on its own buoyancy and was towed up the Mississippi and Ohio rivers to its final destination at Vanceburg, Kentucky. Subsequent to the successful Vanceburg experience in the early eighties, other low-head hydro plants were prefabricated [89ENR]. Such applications of prefabrication have proven that it is a viable alternative to the conventional way of construction in the dry. Prefabrication has thus become another technique for dam construction, particularly for sites exposed to challenging environmental conditions.

Construction in the wet of large numbers of sluices can be achieved economically. For instance, with a linked-basins plant, the powerhouse would be built in between the two contiguous basins where opportunities may well exist to build that powerhouse in the dry such as for instance at the Derby plant, contemplated for construction in Australia, [00New]. The remaining task is then to cut off the two basins from the sea. The closing of such tidal estuaries is generally relatively easy at the start but becomes more and more difficult as the gap to be closed gets narrower. Quite often special techniques are used to achieve final closure, such as the use of temporary sluice caissons which would let the water flow freely in and out of the basin. When all such sluice caissons are in place, closure would be achieved at slack tide by closing all openings in all sluice caissons simultaneously. Subsequently these temporary sluice caissons are buried in the dike structure which is then covered with armor stone to protect it against the onslaught of ocean storms. For any major linked-basins plant which might be built in the future, *permanent* sluice caissons could be used instead of the *temporary* caissons. And in order to achieve ample sluice capacity, construction procedures might be streamlined by placing a great number of such identical sluice caissons. During the Fundy studies it was estimated that for *conventional*, rock-filled dikes, 66% of the cost was in armor stone. This is not surprising since blocks of armor stone must be quarried, transported and placed one by one. In places with a large tidal range, a large proportion of a dike’s slope requires protection by armor. The placement of one permanent caisson would eliminate the need for the placement of many hundreds of pieces of armor. Placing prefabricated caissons in large numbers might therefore well prove to be more economical than building a conventional dike structure. In that way a very large sluice capacity is achieved resulting in minimal energy and head losses due to sluicing.

2.5.7.3 Power plant design

The key question governing the design of any TPP is to determine for which sluicing and generating capacity the plant is to be designed. For a single high-basin TPP, a systematic trial-and-error search for the installed capacity with the lowest unit cost of energy can be carried out as illustrated in Fig. 2.5.20. The optimization curve as shown is typically quite flat. This means that a higher installed capacity will yield more energy at a slightly higher unit cost. In future years, such additional energy might well be desirable. This means that, *if at all possible, a single high-basin TPP should be so designed that additional sluicing and generating capacity can be readily added at some future date.*

A similar conclusion was reached for a single, double-effect TPP as the following example will make clear: At Cobequid Bay in the Bay of Fundy, a single basin, double-effect TPP with a net installed capacity of 100 bulb turbines with a diameter of 7.5 m would produce 11854 GWh of energy per year at a unit cost of 2.7 ¢/kWh (in terms of US$ of the year 2000). The maximum net installed capacity that the site would be capable to accommodate would be of the order of 200 of such bulb units with no sluices. For such a net installed capacity, the amount of energy produced per year would be 17425 GWh at a unit price of 3.2 ¢/kWh. The way in which the unit cost of energy would vary as a function of the installed net generating capacity is shown in Fig. 2.5.21. These costs are based on data from [77Bay], updated on the basis of Bureau of Reclamation Construction Cost Trends to the level of the year 2000. The cost curve is quite flat between 100 and 200 net-units installed, the unit price going up gradually from 2.7 to 3.2 ¢/kWh. The gross installed capacity was assumed to be 5% higher than the net.

Figure 2.5.21 also shows the results of an academic exercise, i.e. what would happen to energy production and costs if up to 100 additional units were to be installed. The lessons learned from this study are to aim for flexibility, simplicity and standardization.

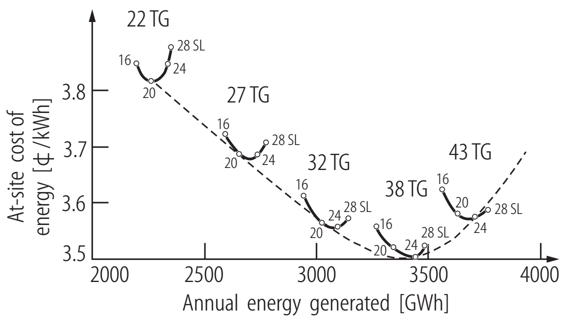

Fig. 2.5.20. Single high-basin TPP curve to determine the number of turbine-generator units and matching number of sluices to produce energy *at the lowest cost per kWh.* TG - turbine generator unit; SL - sluice. With a certain number of TGs, the number of SLs was varied from 16 to 28. As a result, 38 TGs with 24 SLs produce energy at the minimum cost of 3.5 ¢/kWh. The curve relates to one of the sites in Canada's Bay of Fundy (costs converted to US$ values of 2000) [77Bay p. 171].

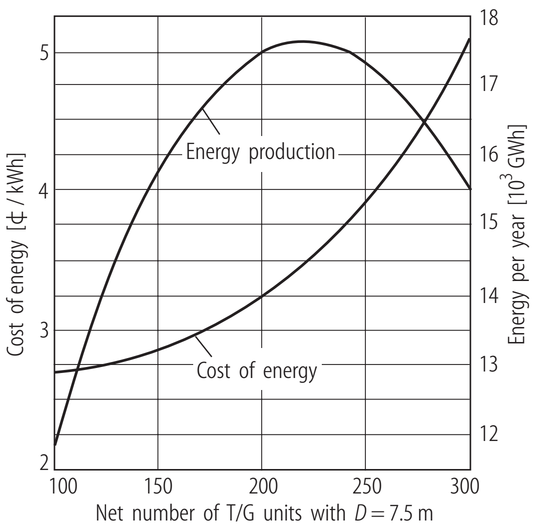

Fig. 2.5.21. Bay of Fundy, Cobequid Bay developed as a single basin, double-effect TPP. Energy production and cost of energy as functions of the net installed capacity in terms of the number of turbine-generator units of 7.5 m runner diameter. No sluices. All water flowing in or out of the basin passes through the turbines. Turbines operate in double effect in the turbining or sluicing mode or are closed so as not to pass any water.

2.5.7.4 Sluiceway design

As noted in Sect. 2.5.6.1.6, one of the lessons learned from La Rance is that in order for a new biological equilibrium to develop within a newly created tidal power basin, regularity in operating the plant will be essential. TPPs of the future should therefore be consistently operated either as a single high-basin plant; as a single low-basin plant; as a single basin double-effect plant or as a linked-basins plant. When sluices are required for either filling or emptying a basin, they should operate in only one direction. This means that the simplest and oldest type of sluice gate, the flap gate, should suffice. During the late 16th and early 17th century, wooden flap gates were installed by French settlers in wooden culverts, set in low dikes which were built to protect farmlands along the Bay of Fundy from flooding. These "aboideaux" released excess water into the Bay of Fundy during low tide. Today, millions of flap gates perform their services quietly and automatically all around the world as check valves. Large flap gates, as would be desirable for a TPP, have not yet been built. What makes flap gates attractive is their inherent simplicity, automatic operation and avoidance of operating mechanisms and controls. Design challenges to be met are achievement of hydraulic efficiency and avoidance of erratic openings and closures when water levels on both sides of a gate are almost equal.

Sluices for a single basin double-effect TPP would have to operate in both directions and would therefore be more costly to build and operate. Such sluices however can be and therefore should be avoided in accordance with the first rule-of-thumb for choosing the right kind of TPP: "Keep it simple" (see Sect. 2.5.8).

2.5.7.5 Numerical, hydraulic and hybrid models as tools for design and construction planning

A simple but adequate modeling technique to assess the annual energy production potential of TPPs was presented in Sect. 2.5.4. More detailed techniques for simulating the operation of TPPs are presented in [97Ber, Chap. 6/7], [87Wil] and [82Wil].

Having decided on the scope of a planned TPP, the question arises to what extent such a plant might affect the tidal regime in the greater tidal basin outside the plant's own barrage(s). Obtaining an answer to that question requires the mathematical modeling of the greater tidal basin in which the contemplated plant would be located. This type of model is far more complex than those which simulate the operation of the plant properly and are described in [91Bak, Ch. 9], [90Gre], [85KuL], [83Gre], [77Gre], [74Hea] and [72Hea].

When it comes to construction planning, particularly when large-scale marine construction operations such as the placing of prefabricated caissons in an ocean-tidal environment are contemplated, the execution of such planned operations on a small scale in a hydraulic laboratory setting becomes advisable. When the planned construction operations are of a scale which would affect the tidal regime in the larger tidal basin around the contemplated TPP, then the use of a hybrid model becomes desirable. Such a model is a combination of a physical hydraulic model with a mathematical tidal regime model to provide, in real time, the border conditions for the physical model. In other words, as the simulated construction process develops in the laboratory, the mathematical tidal regime model will analyze how the changes in the resonant tidal system will affect the dynamics of the tides. That information is sent back to the physical model in the form of changed border conditions. Such a hybrid model was developed and tested in the Hydraulics Laboratory of Canada's National Research Council in Ottawa. For further details refer to [81Arg], [81Fun], [81Rah] and [80Pra].

2.5.8 Some rules-of-thumb for assessing tidal power potentials

Over the last thirty five years, several TPPs have been operated and numerous feasibility studies have been prepared. Many lessons were learned during that period and are likely to remain valid for the next few years. The authors endeavored to condense those lessons into a few rules of thumb which might assist those wishing to locate suitable sites for tidal power development and to evaluate the tidal energy potential of those sites.

A) *Keep it simple*
Favor the simple solutions when comparing alternatives.

B) *Site selection*
- Consider sites which provide at least one natural tidal basin. Having to construct basins artificially means starting off with a severe handicap.
- For a site with two contiguous basins of more or less equal size, consider building a linked-basins TPP.
- When two basins which are of different size or not contiguous are available for development, consider a paired-basins scheme.
- Avoid TPPs with more than two basins. With such schemes the water is forced to pass through numerous sluice structures, losing head at each passing which tidal power, being low-head-hydro, can ill afford.

C) *Design for Energy, not Capacity*
Design, build and operate a TPP for maximum energy production. Manipulating a TPP to provide power on demand results in energy losses and has, on numerous occasions, been proven to be uneconomical. In addition, operating a TPP to meet market demand results in an erratic operating schedule which is likely to be detrimental to the environment.

D) *Type of TPP*

- For a single-basin site with $R_{mean} \leq 9.0$ m, consider a single, high-basin plant. Such a plant would produce two blocks of energy per moon-day.
- If absorption of the tidal energy into the surrounding utility system is going to be a problem, consider a single basin, double-effect TPP, which would, at these tidal ranges, produce less energy but in the form of four rather than two blocks per day.
- For a single-basin site with $R_{mean} > 9$ m, consider a single, double-effect TPP.
- For a site where a linked-basins scheme might be feasible, consider a two stage development. In stage I, build a single, high-basin TPP with large sluicing capacity. Stage II then consists of the creation of the low basin by constructing a barrage equipped with large-capacity dewatering sluices. This completes the linked-basins TPP.
- For a location where a paired-basins scheme seems feasible and where $R_{mean} < 9.0$ m, consider a paired-basins scheme with one high- and one low-basin TPP. In this way, one plant would produce energy on the incoming tide, the other on the outgoing tide, resulting in four blocks of energy per moon-day.
- In the event $R_{mean} \geq 9.0$ m, consider a paired-basins scheme in which both basins operate in double effect, producing four blocks of energy per day. This arrangement could become particularly attractive if the two basins are so far apart that there is an appreciable difference in the tidal phases between the two sites. A phase difference of two hours would result in a continuous power supply while operating each plant individually for maximum energy production.

E) *Establishing the lower limit of a TPPs installed capacity*
If the criterion governing the choice of generating capacity is to achieve tidal energy at the lowest possible cost per kWh, then the following guidelines will be helpful in starting up a trial-and-error approach to achieving the objective:

- For a single, high-basin plant, choose a net installed capacity in [MW] of approximately 0.09 times the site's annual natural energy expressed in [GWh] as a first trial. Choose a rated head of $H_{rated} \approx 0.66\ R_{mean}$ (for conventional Bulb or Straflo™ machines). The same rule applies for phase I of a linked-basins plant as discussed in Sect. 2.5.4.
- For a single, double-effect TPP, choose an installed capacity in [MW] of approximately 0.1 times the site's annual natural energy expressed in [GWh] as a first trial. Choose a rated head of $H_{rated} = 0.5\ R_{mean}$ (for conventional bulb or Straflo™ machines).
- Do not consider the use of Darrieus machines or variations thereof if the head across the machine would ever be in excess of 2 m.
- A systematic, trial-and-error search for the installed capacity with the lowest unit cost of energy can be carried out as in Sect. 2.5.7.3. The optimization curves are typically quite flat which means that a higher installed capacity will yield more energy at a slightly higher unit cost. In future years, such additional energy might well be desirable. This means that, *if at all possible, a TPP should be so designed that additional capacity can be readily added at some future date.*

F) *Pumping*
The net output of a single basin TPP, which includes paired single basins, can be appreciably increased through pumping. Only the plant's turbines should be considered to perform the pumping function. Do not consider building a separate pumping plant. To augment the output of a linked-basins plant through pumping would require the construction of separate pumping plants the economics of which would be doubtful.

G) *Sluices*
Single high-basin schemes, single low-basin schemes and linked-basins schemes all require sluices. These sluices will all work in one direction only, i.e. either to fill a high-basin or to empty a low-basin so that only simple flap gates would be required. Where the sluice structures are to be part of a tidal barrage, consideration should be given to use these sluice structures during the construction period with wide open water passages, letting the water flow freely back and forth so as to achieve a dam closure more easily by keeping velocities during construction of the barrage as low as possible. It would also allow the ecosystem to continue functioning at its own rhythm.

2.5.9 The future of tidal energy

While the world is not yet running out of oil and natural gas, it is becoming more and more dependent on a shrinking number of suppliers. Energy self-sufficiency becomes desirable, apart from the fact that for environmental reasons the burning of conventional fossil fuels should be drastically curtailed. Each and every locality on earth should be looking for sustainable, domestic sources of clean energy such as solar, wind, bio-mass, conventional hydro or tidal energy.

Tidal energy is clean, renewable and as reliable as the movements of sun, earth and moon. It does not flood land which was not flooded before, does not pollute but can even be developed to also benefit agriculture, aquaculture, tourism, recreation and transportation. At the numerous locations around the world where substantial tides exist, TPPs can make significant contributions to the local power grids. Wind energy in the USA fetched a price of 4-5 ¢/kWh in the year 2000. Indications are that tidal energy from the Bay of Fundy can be produced at 3 ¢/kWh. On that basis it would appear that tidal power from Fundy can compete successfully with other forms of renewable energy in the North American energy market. What holds back a decision to proceed at Fundy as at several other locations are

- environmental concerns,
- a lack of confidence in the accuracy of the cost estimate and
- concern about the capability of surrounding electric power systems to absorb the tidal energy which will come in concentrated blocks, two or four times per moon-day.

2.5.9.1 Environmental concerns

The construction and operation of a TPP will result in a changed tidal regime within the TPP basin(s) as well as in the neighboring tidal waters. Experience, particularly at the La Rance TPP, has shown that a sustainable and viable new ecosystem will develop *as long as the mode of operation of the TPP is consistent.* Environmental changes introduced by the construction of a TPP are the least intrusive if the operation of the plant resembles the natural rhythm of the tides as closely as possible, which means that of the four most practical types of TPPs (see Sect. 2.5.3), the single basin, double effect TPP would be the least intrusive.

Experience with the Annapolis TPP has shown that fish mortality caused by passage through the turbine is a serious problem [86Dad]. It would be unacceptable to build a major TPP without first having solved this problem. The establishment of a new, viable and sustainable ecosystem at the expense of existing fish stocks cannot be accepted.

2.5.9.2 Lack of confidence in cost estimates

To gain confidence in TPP cost estimates, it would be advisable to build a few more small plants before the big ones are being tackled.

2.5.9.3 Concern about the value of tidal energy

While this aspect of tidal energy has become over-exposed, it is often forgotten that tidal power operates with the reliability of our solar system to deliver a given number of GWh per year. Tidal power has what conventional Hydro is lacking, namely reliability and predictability. Therefore, conventional Hydro with storage capacity and tidal power are perfect complements to each other.

Each energy market has its own characteristics which will determine what role tidal power might play in that market. France, with an appreciable tidal power potential, has an EDF system which is heavy on nuclear energy, a must-run energy producer. Such plants do not have the flexibility to complement each other so that the tidal power development in France may be difficult in the foreseeable future.

The presently proposed TPP for Derby in north-western Australia finds itself in competition with the development of natural gas resources in the same area. The same applies to Fundy tidal power in Canada and the USA. Rather than looking at these two sources of energy as competitive, they should be viewed as supplementary which, when properly combined, could provide energy self-sufficiency for north-western Australia and north-eastern North America for many years to come.

China, which over the last forty years experimented actively with several TPPs, is poised to develop four substantial TPPs, one each at Leqinwan, Jiantiaogang, Bachimen and Luoyanwan [01LiZ].

New efficient and economical energy storage systems are being developed and could in future years be relied upon to make tidal power acceptable to any utility system.

At present there are clear indications that the production of hydrogen and oxygen through electrolysis and the de-salination of sea water will become major industries. Tidal power would be well suited to provide the energy for such energy-intensive yet simple processes.

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