CONSTRUCTION

OF THE CLEAN-COAL BD3 POWER PLANT UNIT

The retrofit of BD3 to convert from old technology to clean coal incorporating PCC was divided into four distinct, but related, projects:

1 / Power Plant Island (Upgrades and Replacements)

2 / Integration of the Power Plant with the Capture Plant (New)

3 / CANSOLV SO_2 and CO_2 Capture Plant (New)

4 / CO_2 Pipeline to geological injection sites (New)

Construction of the capture plant began in April 2011. Construction of the upgrades to the power plant was intentionally delayed for two reasons: manpower availability (staggered construction would put less strain on skilled trades availability) and long lead time on equipment orders (notably the steam turbine). Power plant construction began in February 2013 after the planned shutdown of BD3.

CONTRACTING

SaskPower entered into fixed-price-and-schedule Engineering, Procurement and Construction (EPC) contracts based on blocks of construction packages with Babcock and Wilcox for the boiler upgrade[47], and with SNC-Lavalin[48] for the capture plant final design and construction. Hitachi[49] was contracted to supply a new dual-mode steam turbine. SaskPower and its owner's engineer (Stantec[50]) undertook integration of the power plant and the capture plant through use of a design-build approach in order to effectively manage the complex "brown" field construction in the power plant that would have made an EPC approach uncompetitive.

Design-build contracts included the following:

1. Turbine island mechanical installation (AB Western)
2. Flue-gas cooler building (PCL and AECON)
3. Flue gas ducting and utilities bridge (Graham)
4. Supporting infrastructure in the power plant (e.g. elevators, building footing reinforcement, etc.)
5. Control system / simulator design, supply and installation
6. CO_2 pipeline to geological injection sites[51]

OVERALL, the project came in over schedule and over budget. Some contracts were delivered on time and on budget, others were not. This is not an unusual outcome for any project of this scale. The project's budget suffered some unplanned changes due to an inadvertent asbestos release and managing lead paint in the old 1970 boiler building[52], skilled labour shortages, and general construction delays. As one would expect with any major infrastructure project of this nature, SaskPower was, as of mid-2015, still settling outstanding claims with some of its vendors.

In future, modularization of the design and construction would be a more desirable approach to meet QA/QC and cost control needs.

POWER PLANT FINAL DESIGN AND CONSTRUCTION

Prior to any decommissioning and tear down of the pre-existing power unit, the owner's engineer, Stantec, completed a 3D computer model of the in-situ power plant. Many changes had been implemented since the unit was constructed in 1970, so the original blue prints were far from accurate. This 3D model was critical to enabling what-if modeling during design, made the implementation of changes to the plant far simpler during construction, and permitted any construction errors to be caught early and rectified.

SaskPower designed a 150 MW power plant that they had anticipated in 2009 would generate 90 MW of net power. Through design optimization and efficient integration of the capture plant with the power plant, SaskPower ultimately constructed a 161 MW power plant that will deliver approximately 120 MW to the power grid when the CO_2 capture plant is operated. The optimization and efficiency gains in power generation that reduced the burden of SO_2/CO_2 capture and maximized power generation were achieved in tiny increments—each one was a rewarding accomplishment. The entire accumulation of power improvements was a stellar achievement.

Ultimately, the parasitic load of PCC was reduced by one-third compared to what was expected at the outset of designing the BD3 retrofit in 2009. The key to this achievement was focusing on optimization of power generation and secondarily considering capture plant performance. Additionally, any economical opportunity to capture otherwise lost energy in either plant by conversion to power was seized.

At any point in the power plant design where there was a risk that power would not be generated due to uncertain capture plant performance, redundancy was designed and engineered into the power plant. This was considered "mission critical risk management". Through use of this approach, SaskPower focused closely on its core mission as a power utility.

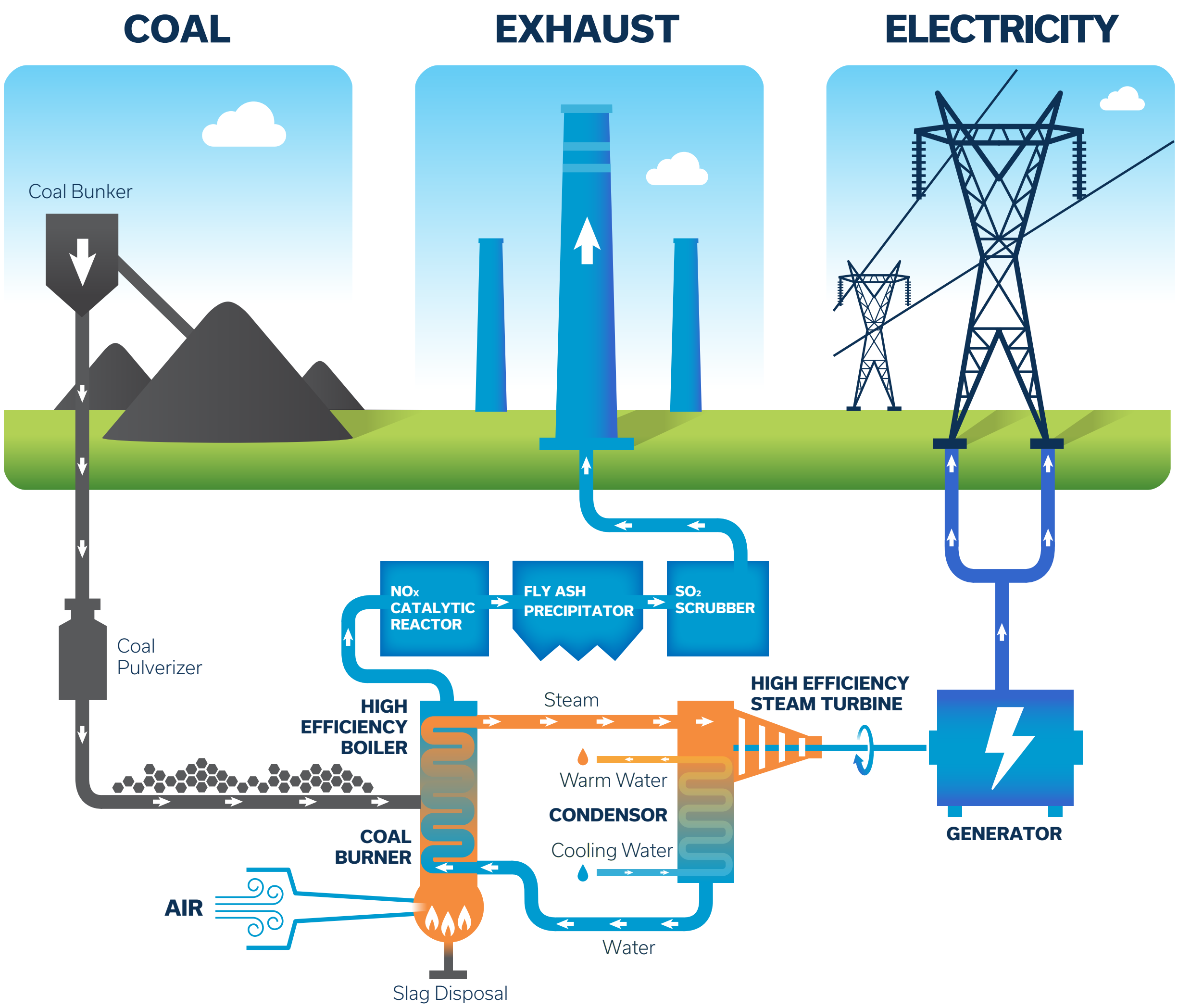
Two major upgrades were undertaken in the power plant:

> The ***boiler*** was upgraded from 1000F to 1050F, and contained significantly more surface area to increase the efficiency of the boiler compared to its performance prior to retrofit. The upgrade of the boiler was accomplished by removal of the boiler's internal heat transfer components and effectively rebuild a new boiler. Due to the additional weight of the upgraded boiler, this process was complicated by the necessity of reinforcement of the columns that support the boiler's weight from the top of the building to the footings.

> The 1969 ***turbine*** was replaced with a modern Hitachi, dual-mode turbine that incorporated better steam and thermal integration, as well as the capability to handle power up or down of the capture plant. Given the requirement for stable and secure power, the power plant was required to operate at full load whether or not the capture plant was in operation, and had to remain operational if the capture plant was suddenly turned on or off. This had a major impact on the turbine selection.

> The power unit's output in non-capture mode was increased by 11.1 MW (7.4%) over the original retrofit design as a result of the combined improvements in the boiler and the turbine.

FIGURE 15 | TYPICAL MODERN POWER PLANT PROCESS FLOW DIAGRAM



Other improvements to the power plant included:

> The power plant equipment cooling system was converted to a closed loop in order to prevent oil and other contaminants from potential discharge to the Boundary Dam reservoir, and to ensure the new equipment was not contaminated by the organic material that may be present in the reservoir water intake.

> A complete rework of the piping throughout the power plant was undertaken.

A typical modern power plant process flow diagram is shown in Figure 15.

The parasitic load of PCC was reduced by one-third compared to what was expected at the outset of designing the BD3 retrofit.

INTEGRATION OF THE POWER PLANT AND THE SO_2/CO_2 CAPTURE PLANT

The connections and interactions between the power plant and the capture plant were an area of intense focus from concept through design and engineering and then construction. This will continue to be fine-tuned over the next year or two to realize improvements in power generation at BD3. This optimization process is typical of the period immediately following the startup of any new power plant.

The following integration equipment components were considered essential to meet the technical specifications of the capture plant and to mitigate technical risk since the CANSOLV CO_2 capture process had not yet been operated at commercial scale:

Flue-gas cooling was required to reduce the flue gas temperature to the operation temperature required by the CANSOLV SO_2 capture process. SaskPower enhanced this process by addition of a polymer heat exchanger to recover heat from the cooling process. The captured heat could then be used to pre-heat the condenser water used for steam generation in the power plant, which thereby improved the efficiency of power generation by about 3.5 MW through reduction of the demand on low pressure feed-water heaters during capture plant operation.

A Direct-Contact Cooler (DCC) was added as a pre-scrubber to further reduce flue gas temperature prior to entry to the capture plant, and to remove particulates and other contaminants that could negatively impact the performance of the amines in the SO_2 and CO_2 absorption towers. Recall: the feedstock for the capture plant was the flue gas. Its constituent specifications were required by CANSOLV in order to meet performance guaranties for the capture processes. Preconditioning by the DCC was considered an essential step to meet those flue gas specifications.

Steam supply from the power plant to the amine reboilers presented a challenge to the design and engineering teams. Steam flow would start or stop when the capture plant was turned on or off, that would complicate the requirements of the steam turbine power generator. Temperature control was critical at the capture plant's reboilers to prevent degradation of the amines and production of toxic by-products. This is one area that continues to be worked on during 2015–2016 to ensure optimal functionality.

Steam supply from the power plant to the amine reboilers presented a challenge to the design and engineering teams.

A flue-gas diverter was installed to divert flue gas to the pre-existing BD3 stack when the capture plant was not in operation, which would be the case when the power plant was operating at less than 50% load. The diverter dampers were designed to allow incremental adjustment between fully open to the carbon capture plant, and fully open to the stack. This adjustability allowed for smoother start-up and shutdown, and enabled the capture plant to be run at partial capacity independent of the power plant.

A new feed water system was installed due to additional use of steam by the capture plant and its significant impact on steam pressures in the turbine and feed water heaters.

CAPTURE PLANT

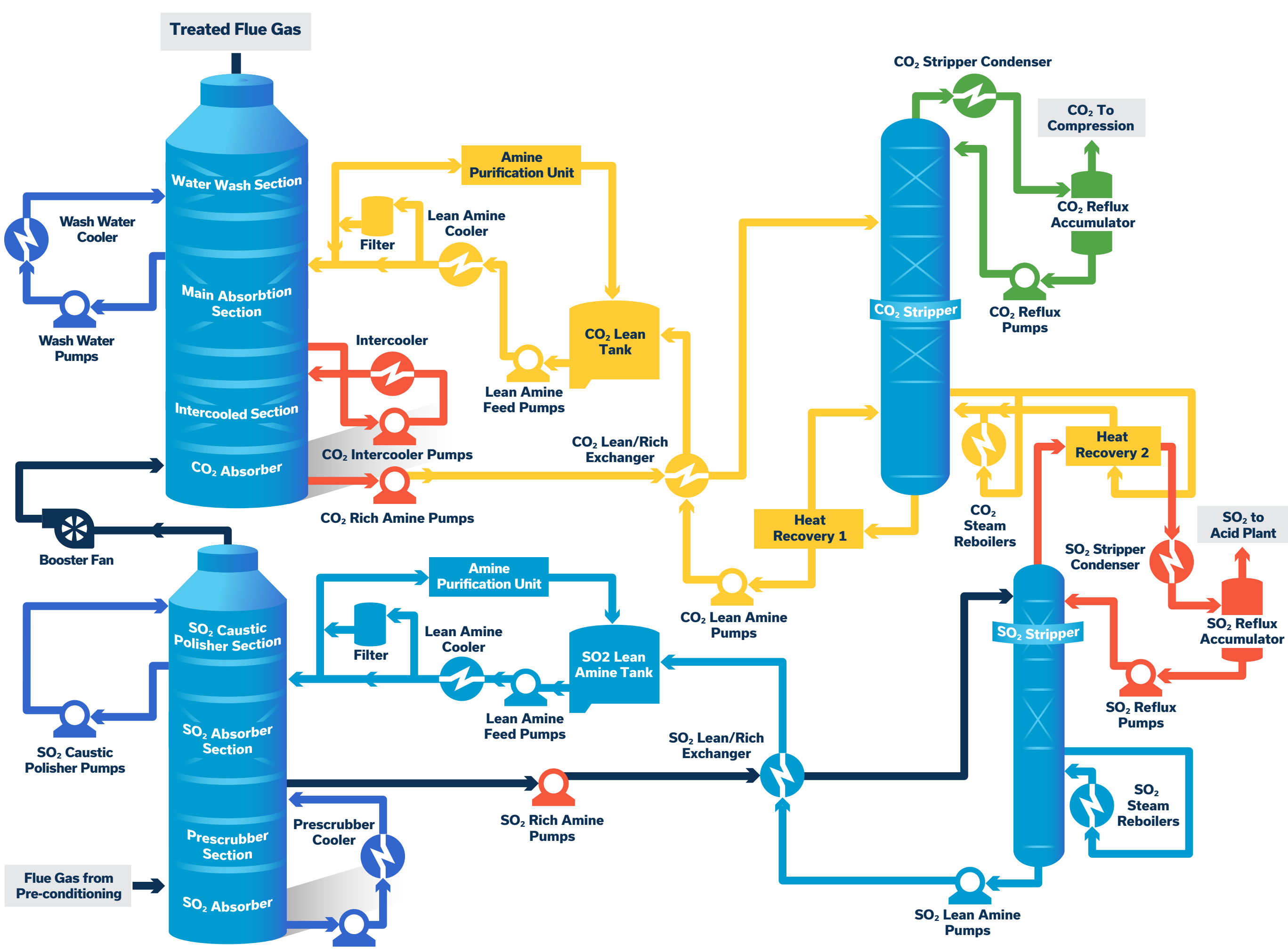
SNC-Lavalin performed the detailed EPC of the overall capture plant, with CANSOLV providing the SO_2 and CO_2 capture technology, including the process design and related performance package for the capture facility. The EPC was divided into three sub-facilities:

1 / Capture facility

2 / Heat rejection system

3 / CO_2 compression and balance of the plant

FIGURE 16 | SHELL CANSOLV TECHNOLOGIES' COMBINED SO_2 AND CO_2 CAPTURE PROCESS



CONSTRUCTION of the capture plant began in April 2011. The following processes and equipment/infrastructure are associated with the capture plant and its by-products:

> After scrubbing SO_2 from the flue gas in the amine absorption process, the clean SO_2 is sent to a new acid plant to produce sulphuric acid, which is then shipped to end users via an on-site truck-loading facility.

> Following CO_2 capture from the flue gas, the CO_2 is dehydrated, and compressed to produce a supercritical, 99% pure CO_2 product lacking the water, hydrogen sulphide and other trace impurities present in CO_2 from the Dakota Gasification Facility (DGC) (these undesirable constituents are due to the nature of the latter's coal gasification process)[53] . The compressor used at BD3 is similar to those that have been in service at DGC in Beulah, North Dakota since 2000. It is an eight stage, integral-geared centrifugal compressor, with a capacity of 55 mmscf/d (1.58 million m^3/d) and electricity driven by a 14.5 MW fixed-speed motor. The supercritical CO_2 is pipelined to the injection site hosting Aquistore and Weyburn for CO_2 geological storage and CO_2–EOR, respectively.

> The flue gas that has been stripped of CO_2, SO_2, particulates and other contaminants is water washed and released to the atmosphere from the capture plant through a new venting stack at the top of the CO_2 absorber vessel.

The capture plant was originally intended to be operated remotely from the power plant with limited internal staff. However, during construction it was recognized that controlling the chemistry in the capture plant would be critical to its performance. Furthermore, when data was received from the CO_2 Technology Centre Mongstad[54] in 2013–14, it was recognized that SaskPower would need to carefully manage amine chemistry, and study its reactions and side-reactions, to assist in developing strategies to better manage the risk associated with off-specification behavior.

Consequently, the capture plant has its own custom on-site laboratory that is used for quality control and assurance in the capture plant and for research purposes to study nitrosamine chemistry and amine solvent reactions, particularly those facilitated by the presence of any flue gas contaminants entering the capture plant. The capture plant manager is a chemist and works closely with the on-site lab and other SaskPower labs to develop knowledge and understanding of the amine chemistry associated with the SO_2 and CO_2 capture absorber systems.

OVERALL EFFICIENCY **IMPROVEMENTS**

All of the iterations to maximize power generation and minimize parasitic load of SO_2 and CO_2 capture paid off. SaskPower will be able to generate 115–120 MW of power using a 161 MW turbine once the construction deficiencies have been rectified and the initial troubleshooting and optimization have been completed. The improvements as of Spring 2015 are shown in Figure 17.

CO_2 **PIPELINE**

SaskPower constructed, owns and operates a custom-built, carbon steel, supercritical CO_2 pipeline that runs approximately 8 km to the northern edge of its property. Cenovus built the pipeline from that point to its Weyburn CO_2–EOR operation. Just prior to the change of custody at the property line, a 2 km pipeline leg runs to SaskPower's CO_2 injection site at its Carbon Storage and Research Centre that is located on the Boundary Dam Power Station property. That pipeline leg is capable of handling the entire volume of CO_2 produced at the power station should that become necessary or desirable at some point in the future.

FIGURE 17 | OPTIMIZING THE PERFORMANCE OF BD3 TO MAXIMIZE POWER GENERATION

Viability requires minimizing...

- thermal energy requirements
- parasitic electrical load

- POWER TO GRID (112 MW)
- EXISTING PARASITIC LOAD (11 MW)
- COMPRESSION (15 MW)
- CAPTURE CO_2, SO_2 (9 MW)
- AMINE & HEAT REGENERATION (14 MW)

SAFETY MANAGEMENT

SaskPower places the highest priority on safety in all of its construction projects. The very large size of the BD3 construction work force created a more challenging situation than usual. Numerous proactive and day-to-day steps were taken to ensure the highest possible safety standard was maintained.

Parallel to the construction activities, there was a keen focus on operational readiness. A dedicated HSE team prepared new standard operating procedures (SOPs) for the capture plant and worked with the operations team to perform rigorous HAZOPs to identify and rectify any anticipated hazards or operational issues. The overarching philosophies of the safety process were the following:

> A "zero leak" standard for power plant and capture plant operations

> Development and delivery of an unprecedented training program that led to all operators being trained and proficient prior to commissioning and startup. The training program constituted over 80 modules on safety and fully utilized the custom process simulator.

This safety preparation took over three years to accomplish but ultimately set up the combined power plant and capture plant operating team for success.

The ICCS project had a stellar safety record. There were no lost time injuries during the 4.5 million person hours of construction time. That is not to state there were no construction-related safety hurdles to overcome. Those safety challenges were successfully resolved, and included:

During the 4.5 million person hours of construction time there were no lost-time injuries.

> Despite a rigorous asbestos abatement program conducted at the Boundary Dam Power Plant in the years leading up to the power plant shutdown, there was an asbestos release from the old 1970 boiler building during the power plant construction. This resulted in a significant work stoppage to ensure asbestos cleanup that lasted several weeks.

> Due to a poor safety track record, the man lifts were decommissioned at the site just prior to the main construction period in the power plant. This necessitated construction of temporary elevators in the middle of the BD3 unit, and outside the plant walls to allow the efficient movement/circulation of tradespeople and materials at the power plant construction site, to thereby minimize impact to the overall construction schedule.

> Amine capture solvents and chemistry were foreign to the company and its operators. Consequently, SaskPower developed a world-class chemical safety program and set of standard operating procedures (SOPs). Due to its unfamiliarity with the subject matter, the company was able to think "outside the box" during SOP development from its perspective as a non-chemical user prior to the start-up of the capture plant.

RISK MANAGEMENT

Risk was managed throughout design, engineering and construction with rigorous use of risk registers. Risk management was a daily focus during construction. There was continual monitoring of construction productivity, coupled with ongoing labour availability risk assessment and planning.

Accommodation risk was a concern. Due to labour shortages, SaskPower had to ensure it was an "employer of choice". This meant compensation had to be maximized to attract construction labour, which included subsistence allowances. Consequently, SaskPower had to find cost-effective, off-site accommodations for up to 1500 staff at a time when the oil industry also had peak labour demand in the region. Temporary on-site labour accommodations were not an option and were not utilized.

PERMITTING

Throughout the period from 2008 to late 2014, that spanned the first request for capture technology proposals in 2008 through design to engineering and finally through construction of the BD3 retrofit, SaskPower worked closely with the Saskatchewan Ministry of Environment on regulatory permits. Any changes in the design that could impact permitting were promptly provided to the Ministry's Assessment Branch and any issues that might impact permits were transmitted internally within the Ministry to the Permitting Branch through a seamless review/assess/approve/update process. Despite the unusual first-time nature of the project, the entire reporting and permitting process was swift and efficient.

The permitting and regulatory process associated with the CO_2 injection and monitoring wells at the SaskPower Carbon Storage and Research Centre regarding deep saline storage/disposal of CO_2 was handled similarly, although the permits for the injection and monitoring wells were issued by the Ministry of Economy that regulated oil and gas activity in Saskatchewan and hence all deep well drilling activity.

KNOWLEDGE BUILDING

Throughout the entire BD3 ICCS project, SaskPower managed uncertainty well through a "can-do" attitude that has been ingrained in its corporate culture. A lot of activities were undertaken in parallel, that led to schedule gains at the cost of efficiency and some re-work. Effective communication was the key to a productive work environment. Challenges were observed from many different angles and resolution was achieved as a team effort rather than by any one particular individual.

As a result of the BD3 ICCS project, including its prerequisite exploratory work, SaskPower has developed a strong and capable engineering team. Knowledge and insights have been carefully documented, along with the entire BD3 retrofit design, to support option analyses for potential future coal-fired power plant retrofits. In fact, this effort is already assisting the business case decision planning regarding BD4 and BD5 that is ongoing as of mid-2015. An illustration of the time frame for CO_2 capture technology maturation within SaskPower is shown in Figure 18 on the next page.

FIGURE 18

TIMELINE OF CO_2 CAPTURE AND STORAGE TECHNOLOGY MATURATION AT SASKPOWER

1976 | 1980 | 1986 | 1990 | 1996

1978
Chevron SACROC CO_2–EOR begins

1984
Shell and Pan Canadian seek CO_2 from SaskPower for Midale and Weyburn

1985/86
Early amine capture pilot plant at BD6

IGCC

1994
SaskPower gains IGCC license and permit for Shand 2

1995/96
Shell operates CO_2–EOR pilot at Midale

1996
CanmetENERGY™ oxyfuel com-bustion piloting begins

1996
SaskPower begins oxyfuel screening study for Shand 2

1999
CO_2 pipeline from DGC to Weyburn area completed

2000
Pan Canadian operates commercial CO_2–EOR at Weyburn

2000
IEAGHG™ Weyburn CO_2 monitoring project begins

2001
CCPC begins

2002
SaskPower begins operating first NGCC power plant

2002
Natural gas prices soar

2004
CCPC demonstrates clean coal competitive with NGCC

2005/06
SaskPower collects commercial pricing for oxyfuel at Shand 2

MID 2007
SaskPower decides to plan for a PCC retrofit at BD3

EARLY 2008
Federal funding for BD3 retrofit engineering

MID 2008
RFP for PCC CO_2 Absorption Capture Technologies

2009
CANSOLV SO_2-CO_2 capture system selected for BD3

LATE 2010
BD3 power plant rebuild approved by CIC

APRIL 2011
BD3 capture plant approved by CIC

APRIL 2011
Capture plant construction begins

FEB 2013
Power Plant Rebuild Construction Begins

JUNE 2014
BD3 Rebuilt Power Unit Generates First Power

OCT 2014
BD3 capture plant generates first CO_2

2015
BD3 retrofit improvements continue

APRIL 2015
Aquistore begins monitoring injected CO_2

JULY 2015
CEPA regulation requires CCS at old coal power plants in Canada

2015/16
Business case for BD4 and BD5 retrofits developed

2000 | 2006 | 2010 | 2016